Adaptive Color in Dynamic Mapping:
A Method for Predictable Color Modifications

by Didier Bardon

Graduate of Ecole Nationnale Supérieure des Arts Décoratifs
Paris, France, (1980).

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Abstract

Graphic display of information is becoming increasingly interactive and dynamic. The images that are offered can evolve, in real time, rapidly. The graphic control that insures the effectiveness of these dynamic images needs to be pursued throughout the course of their evolution. Automated graphic control modules should be made capable of maintaining graphic quality as users interact with the display.

In this work, a method for managing color in dynamic images is proposed. It enables color to play several roles concurrently, in the dynamic image. Examples are: perform semantic tasks like identification and grouping of graphic objects, create perceptual levels in the image and maintain discernability among objects as they evolve. This method is based on the dynamic relationship that exists between the image and the color space that underlies it. The global color configuration in the image is represented by its mapping into the Munsell color space. This representation is used to guide color choices and modifications with predictable visual effects.

The method of color management is implemented in a graphic application system which simulates the images and interactions that dynamic mapping environments can be expected to offer. The system main goal is to help obtain the visual knowledge that should underlay the method of color management.

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The following people have served as readers for this thesis.

Walter Bender
Principal Research Scientist
MIT Media Laboratory

Debra A. Adams
Member of Research Staff
Xerox Corporation/Palo Alto Research Center

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University of Massachusetts at Boston

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Chapter 1. **Introduction**

"La couleur, suivant les physiciens est une propriété de la lumière, par laquelle elle produit, selon les différentes configurations & vitesses de ses particules, des vibrations sur le nerf optique, qui étant propagées jusqu'au sensorium, affectent l'ame de différentes sensations."

Diderot, Encyclopedie, Tome IX, Partie II *

1. Dynamic maps, two sources of evolution

Dynamic Mapping Environments can be defined by comparison to traditional printed maps. A printed map offers a static presentation of a limited number of information sets. The choice of information is related to the theme of the map and only a limited number of problems can be helped by a single map. The limited graphical capacity of printed maps reduces the quantity of information that can be presented and fosters specialization of their purpose.

Dynamic maps in the electronic medium are not burdened by the same limitations. It is not clear if the graphic capacity is larger for maps displayed on high resolution CRTs than for the printed ones, but the amount of information that can be accessed and displayed electronically is independent of that graphic capacity. Precisely, dynamic maps can be composed in real time and can offer relevant selections of information out of large information bases. This is an important aspect of dynamic mapping. The choice of information being presented can be made to help solve a particular current problem. Then, the choice can be automaticaly modified to follow the decision making process, as answers to queries bring about other, more focused queries. This research approaches dynamic maps as dynamic graphic interfaces with large topographically structured information bases.

Information always evolves with time. If printed maps become obsolete with the passing of time, electronic maps can easily reflect the evolution of information. The evolution of information results in a constant or periodical updating of the values in the geographic data base. Some of evolutions need to be reflected on the display in real time. Examples include air traffic control, forest fire monitoring, medical monitoring. Other applications that do not require real time, can display information in accelerated time for a better understanding. Examples are: economical exchanges, population movements or environmental

* Translations of quotes can be found in the bibliography, page 107.

Figure 1a.

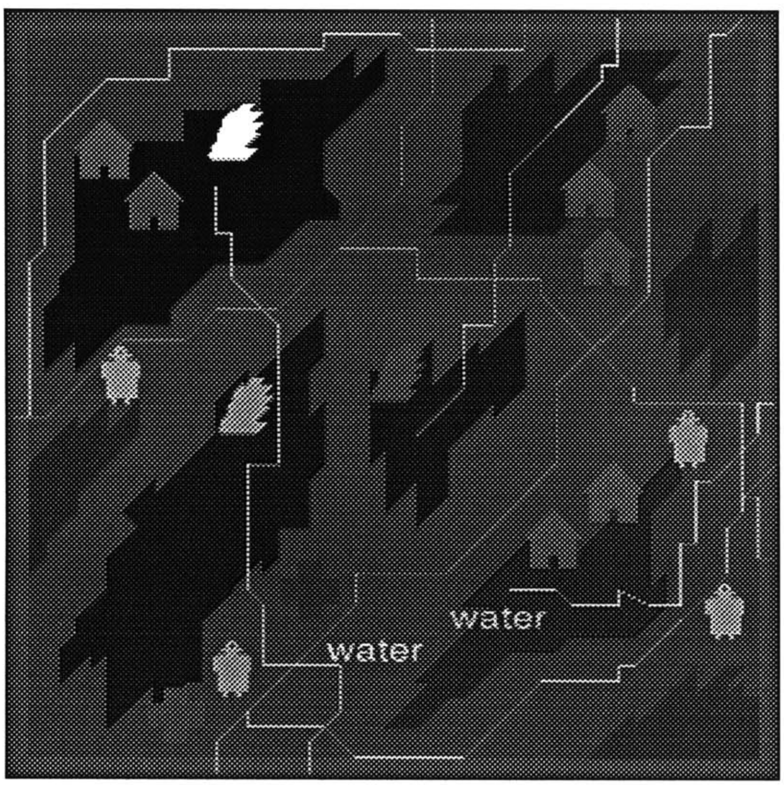

Figure 1b. The image evoloves according to fulfill the current information need. *Color copies of this thesis can be found at the Visible Language Workshop, Media Laboratory, E15-443*

pollution monitoring. In real or virtual time, the ability of the dynamic maps to reflect the evolutions in their underlying information is the second aspect of dynamic mapping that determine our understanding of this kind of electronic display.

Thus, images that will be produced by Dynamic Mapping Environments will be the result of two distinct sources of change. First, the evolving information need of the decision maker. Second, the evolution of the information contained in the underlying information base. We use this understanding of the nature of dynamic maps to define the graphic environment that will support such displays, and to describe the graphic problems that need to be solved if the expectations set forth here are to be fulfilled.

2. An example of dynamic mapping environment

The following is a description of a concrete example of a Dynamic Information Display in use. In this example we will consider only the visual effects of the interaction between the decision maker and the display and the visual effect of the interaction between the underlying information system and the display. Issues concerning the user interface will not be taken into account; as fundamental as they are to dynamic information displays, they are not within the scope of this study. **Figure 1** presents a graphic simulation of this example produced on the experimental system developed during this research.

Let us imagine that the officials in charge during the forest fires at Yellowstone National Park (1990) had used a Dynamic Mapping Application as a support to the management of the crisis. Along the unfolding of events a succession of diverse problems had to be solved that demanded different kinds of information. In most of the cases the common thread of this information was their relation to the topographic structure of the Yellowstone National Park. Decisions had to be made in the domain of security, manpower allocation, water supply allocation, etc. To look at the current situation in terms of security, officials using a Dynamic Mapping Display would have wanted to be presented with a visualization of the location of built-up areas, the location of isolated dwellings, the location and capacity of medical facilities, the road system, the current location and extent of the fires, etc. With the help of such a display imminent crisis could have been discovered and rated by level of emergency (this rating would be entered into the system by the user and reflected visually by the display) (**figure 1 a**). Then, with these facts in hand, the decisions concerning the allocation or reallocation of man power and equipment could have been addressed. New queries would have caused the composition of a modified image. Most of the graphic representations of information sets in the previous state of the display would have been faded into the graphic context while other sets, relevant to the new problem would have been brought into the foreground, i.e., current location of fire fighting unit, location and current state of water supplies etc... **(figure 1b)**. This is an example of the double source of image evolution that will be characteristic of dynamic maps. The display is modified both by the evolving focus of interest of the user and by the underlying system constantly making the display up to date with the current state of the information base.

3. A method of color management and an experimental system

The visual evolution described in the forest fire example, as simple as it may appear, requires the real time control of several graphic aspects of the dynamic image. The transfer of graphic objects sets between visual proeminence and visual ressess is acheived by modifying their colors. The challenge of automatizing such visual processes resides in producing color modifications which intentions are acurately perceived by the viewer. In addition, color modifications have to be made without jeopardizing the semantic use of color in the image, i.e., contributions to the expression of objects grouping and identity. Such visual modifications of the dynamic image will be possible only if all the color relationships in theimage are represented and controlled.

This work proposes a method of management of the color ressources in the dynamic image. It is based on the existing relationship between an image and a perceptually consistant color space. The color of every object in the image maps to a three component vector in the color space. For reasons that will be developed further, the method represents the color relationships of the image into the perceptually consistent Munsell color model.

The method of color management is implemented in an experimental computer graphic application. The color relationships in a prototype dynamic mapping image are controlled through an interface with the Munsell color space. Visual experiments are performed with the purpose of acquiring the graphic knowledge that is necessary to automate the management method. **Figure 2** presents a schematic of the systems components. Color relationships in the image are controlled with a set of interactive tools. The color relationships and the effect

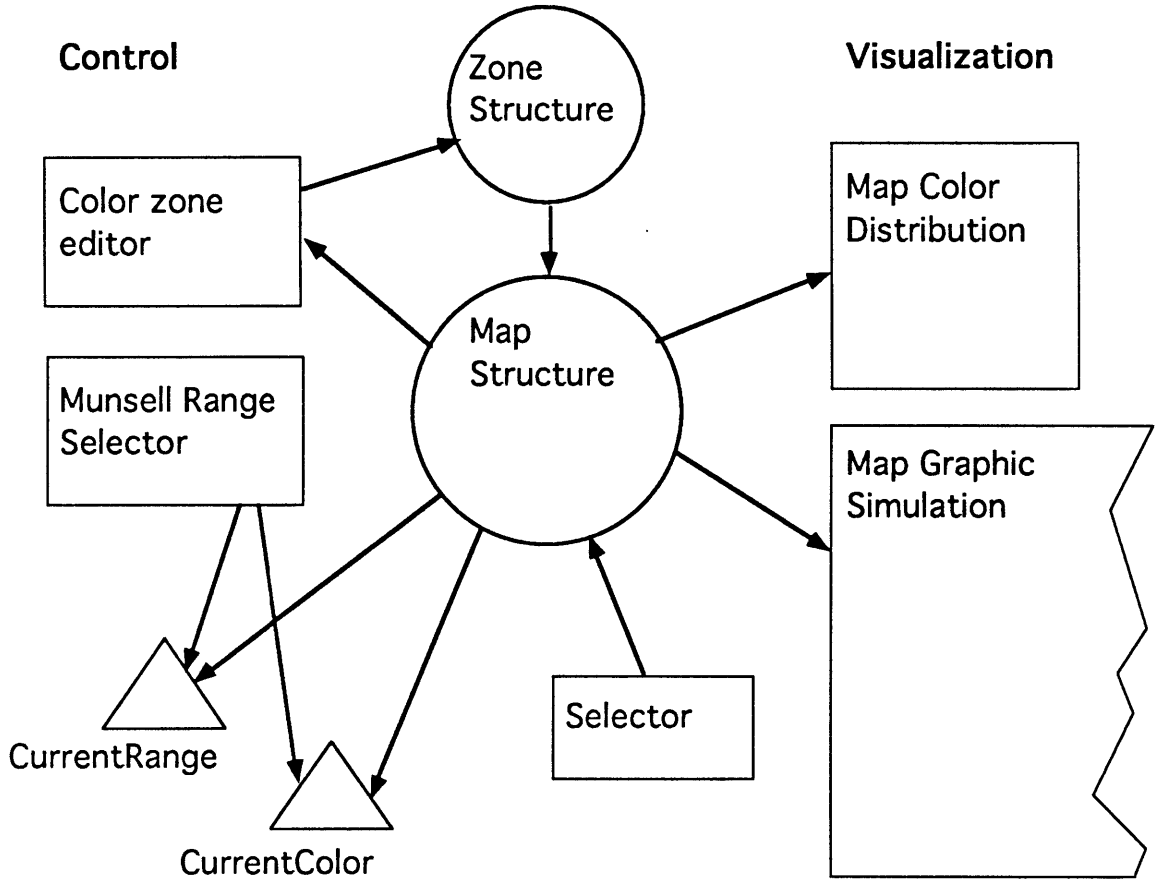

Figure 2. System components

of the color modifications can be visualized in the map graphic simulation. The color relationships in the image and the use of the color ressources made by the image are visible in a 3-d viewport where the Munsell space is represented.

In the following chapters, a definition of Dynamic Mapping Environments will be presented. This understanding will help derive a set of graphic design requirements for this new kind of images. they take into account the particular kind of interactions that they can be expected to support, and the specificity of the visual enviroment offered by the electronic medium. Then the color management method will be presented. The experimental system wil be described in detail. A series of visual experiments will be presented and evaluated. It will be seen that the management method allows the three components of color to be used as three

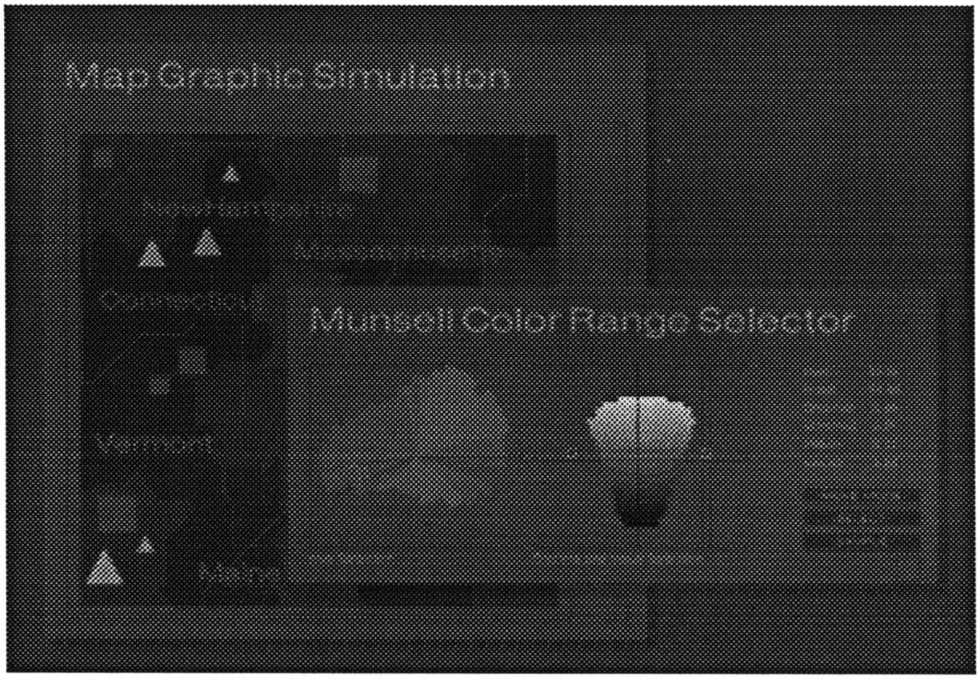

Figure 3. The map graphic simulation with the Munsell color range selector that is used for the control of its color relationships.

Chapter 2. Dynamic mapping environment

"... a mingling of colour and form each with its separate existence, but each blended into common life which is called a picture by the force of the inner need."

Kandinsky on painting.

1. Introduction

New graphic problems

Recent geographic information systems are proposing visual presentations of topographically structured data using state-of-the-art computer graphics. These systems elicit the vast potential of the computer generated image for the visual presentation of information and for computer based assistance to decision making. But so far, technological limitations have kept the amount of dynamics and interactivity proposed by computer visual application at a low level. With the rapid evolution of graphic computing, it can be expected that in the very near future, these systems will be better called Dynamic Mapping Environments. They will be used as visual interfaces to large geographic data bases. User queries will determine the composition of the display. The display will also reflect, in real time, the evolution of the data base itself.

With such dynamic, interactive displays, new graphic design problems are emerging. The evolution of the image can no longer be a pre-scripted sequence of events where the graphic conflicts created by the changes are foreseen and dealt with in advance. When the image evolves through user interaction or automatic update of the underlying information base, unwanted graphic complexity may appear. Graphic elements may become indiscernible, their meaning in the image may be lost. To prevent a degradation of the image to occur as users interact with it, its evolution must be supported by graphic control modules that eliminate graphic conflicts as much as possible. When conflicts do occur, the control modules should be able to detect and solve them. An example of such a module is the Adaptive Text demonstration developed at the Visible Language Workshop, where text labels moving on a complex map background are able to maintain their legibility and a consistent color appearance by adapting to the graphic conditions found at every new locations in the map. [Ishizaki, 1990] [Bardon, 1991].

A global approach to graphic control

The Adaptive Text demonstration solves graphic problem locally as they occur throughout the evolution of the dynamic image. This local approach is likely to play an important role in the graphic control of dynamic mapping image. Nevertheless, it cannot be expected to address the several kind of design problems posed by the control of such dynamic images. In this work, a global approach is proposed. The approach consists of controlling the dynamic image in all its elements and in their interactions. This attitude is in line with the basic principles of graphic design. These principles state that all the elements of an image have to be integrated into a functioning whole. The appearance and visual weight of each element has to be consistent with its role in the image.

In addition to the problems of graphic quality maintenance presented above, a graphic control module has to insure that the dynamic image remains easily understandable at all instants of the interaction, and that the semantic operations that are the essence of static and dynamic mapping are possible. Three class of tasks can be isolated, that have to be performed concurrently, while a dynamic mapping image is being used: *Semantic tasks, Visual ordering tasks, Graphic quality maintenance tasks.*

These tasks have to be performed concurrently by carefully using the limited number of visual variables available: *shape*, *size*, *texture*, *orientation*, *value* (when color is not available), *color*.

The issues related to the assignment of semantic tasks to the five visual variables have been thoroughly researched. Bertin, in his seminal work, gives a classification of the visual variables in view of their competence in performing semantic tasks. He assigns a limited role to color, in comparison to the other variables. Color can efficiently perform tasks of association and selection [Bertin, 1972]. But, this is considering only the semantic tasks. In this work, it is believed that color can be assigned a role in performing tasks of visual ordering and graphic quality maintenance in addition to its limited role in the performance of semantic tasks.

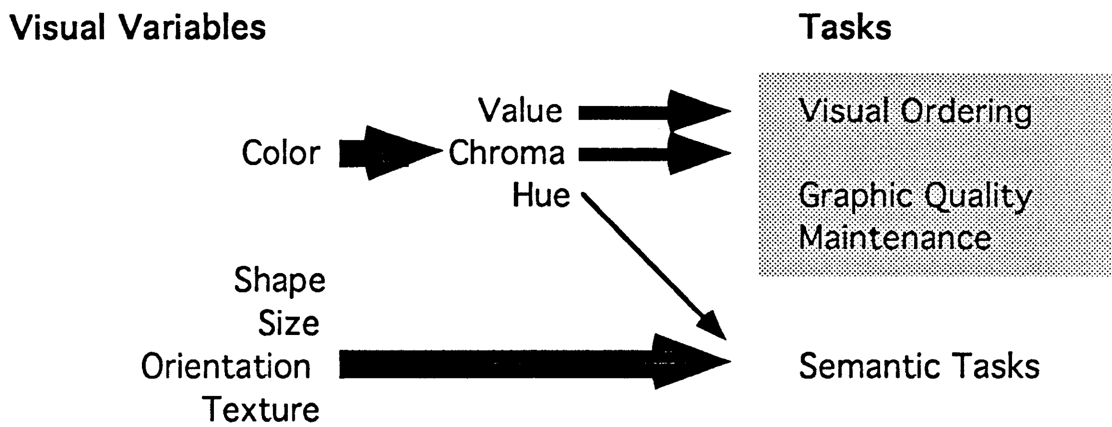

Figure 4. The three components of color can be assigned different tasks in the dynamic image. Value and chroma can be used for the graphically related tasks. Hue can be assigned a limited role in performing semantic tasks.

Hypothesis

The hypothesis, that is at the base of the research presented in this thesis, states that the three components of color, in a perceptually consistent color space, *hue*, *value*, and *chroma* (saturation), can be treated as three independent visual variables. These three color components can be assigned roles in the three categories of tasks related to the control of dynamic mapping displays. The diagram of **figure 4** illustrates the assignments of tasks that is proposed by the hypothesis. Value and saturation are assigned roles in the two graphically related tasks: visual ordering and graphic quality maintenance. Hue is assigned the role in performing semantic tasks that usually belongs to color as a whole in static mapping: association and selection.

Such a multiple role for color in dynamic mapping is possible only if a control of all the colors in the image, and of their relationships, is available. The validation of the hypothesis needs a method for the management of color usage in the dynamic image that seeks to control the global color situation at all times. The method that is proposed here is based on the pre-existing relationships that exists between an image and the color space that supports it. The method uses this relationship to represent the color situation in the image, to organize and control it. It will be explained how the method helps resolve the conflicts inherent to using color to perform three kinds of tasks concurrently.

2. Graphic design requirements of dynamic mapping environments

Interaction with a dynamic mapping environment

In view of the example presented in the previous section, the type of interaction that will take place with dynamic mapping displays can be described and its visual consequences on the dynamic image can be assessed. The interaction with a dynamic mapping is a dialog between decision maker and an information-rich image. This dialog can take place only in the information contained in the image can be extracted easily and rapidly by the decision maker. As a result of this assessment, two main graphic design requirements will be established: first, a visual ordering has to be instated in the image, second, a global approach to the problem of graphic quality maintenance will be taken.

In the example above, users of dynamic mapping display make decisions by comparing different sets of information within an informational context. As the decision making progresses, the display passes through successive states. At every new state, a new information situation is presented to the user. This new image is part of the dialog that is taking place between the user and the geographic display. The information contained in the image should be recoverable rapidly by the user in order to avoid breaking the dialog. The traditional way of encoding information in printed maps requires too much interpretation time to allow the speed and immediacy that seems to be necessary to the type of interaction described in the forest fire monitoring example. The methods that will be used to visually encode information in dynamic mapping will have to be chosen in accordance with this need for rapid information extraction.

The type of images that supports such a decision making process is complex by nature. The graphic objects contained in the image are divided into groups that must be quickly identified by the user. Some groups denote information sets that are involved in the user's current concern. Other groups denote sets that are part of the informational context. All these objects appear over a topographical background which, itself, contains important information. It seems that information needs to be represented at least on three different visual levels: a *foreground*, a *context* and a *background*. By instating a visual order of that kind in the image, the user will be able to quickly discriminate between the groups, and an overwhelming visual complexity will be avoided.

At every new state of the display, the graphic objects in it will assume modified appearance to reflect the evolution of their role in the dialog. Their colors will be affected as well as their locations. As the display evolves, multiple successive modifications of the objects graphic attributes may occur. A degradation of the image quality can be caused by such a complex, unpredictable evolution. For example: the appearance of distinct objects might become too similar or the color of objects might become too close the color of their background, causing visual confusion and losses in discernibility. In this work, this kind of basic graphic problems will be referred to as *graphic quality* maintenance problems. The visual framework within which the evolution of the display will take place should allow the dynamic modifications of graphic objects to happen with a minimum of conflicts. It will be shown how a global approach to solving problem of graphic quality maintenance will help create such a framework.

Rapid extraction of information

Rapid extraction of information helps support a dialog between a user and a dynamic display by preserving the continuity of the interaction. As stated above, a constant clarity of the image will be maintained despite image evolution by an appropriate visual ordering. The continuity of the dialog through time will be maintained by allowing the user to rapidly extract from the image the information contained in it. That continuity is to be maintained if a dialog is to take place at all.

The method of visually encoding information is a principal factor that affects the speed of information recovery from an image. In static or dynamic mapping, information is visually encoded by making careful use of the six available visual variables, i.e., size, value, texture, color, orientation and shape [Bertin, 1982]. Each one of these variables is assigned a precise role in the image. These roles are related to the varying abilities of the human visual system to perceive differences in a given visual variable. The extensive work of Bertin in these matters offers sound guidelines for assigning the correct roles to visual variables in an image. In his work, each one of the six visual variables (retinal variables) are studied, and the information encoding tasks that they can perform best is determined. For instance, shape is able to convey order and quantity, and to perform tasks of selection. Color is assigned a more restricted role. Only tasks of association and selection can be performed well [Bertin, 1983].

Information can be extracted very quickly from images providing that the visual variables are used appropriately. In his work, Bertin describes two different categories of images. The "images to be read" that he qualifies as polysemic, and the "images to be seen" that he qualifies as monosemic. To extract information from a polysemic image, the viewer has to interpret a visual code. This interpretation time (this reading of the image) should be avoided as much as possible to maintain the dialog with the dynamic images. Conversely, information doesn't need to be extracted from a monosemic image, it is immediately perceived without requiring an effort of interpretation (the information is seen, not read). This situation is ideal to support an efficient dialog between a user and a dynamic mapping display.

It is important to note that Bertin's monosemic images are composed in very specific graphic situations. It is not clear yet if images with such efficiency can be composed in a dynamic environment. Nevertheless, Bertin's finding have to be brought to bear to help achieve the requirement of rapid information extraction. An ideal dynamic display will offer monosemic presentations of information at every new state of the interaction.

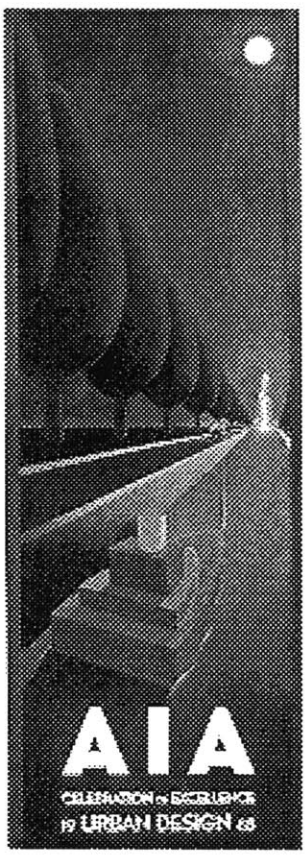

Figure 5. Using color to establish visual ordering in graphic design. The effect of depth in the image is reinforced by giving a bright saturated red to the boat in the foreground. Less saturated colors are used in the background. The headline is the brightest object in the poster.

Visual ordering

Establishing a visual ordering in an image is a basic graphic design practice. It is present in all images that achieve a clear communication. Visual ordering makes the semantic structure of the image visually explicit by giving to each of its elements a visual weight appropriate to its role. At the first glance, the viewer is informed about the structure of the image content. The parsing of the image's elements is helped in very much the same way good enunciation and rhythm of a lecturer helps the listener parse a speech. Usually without his or her knowing, the viewer will be able to immediately grasp the meaning of a visually ordered image **(figure 5)**. If visual ordering is absent, the confusion and the effort necessary to sort the elements turns the viewer away from the image. It is important to notice that the images that are designed for competitive communication environments like advertising images most often show very efficient visual ordering. Since no one really wants to look at an advertisement, this kind of image is usually designed to be crystal clear. The communication environment offered by dynamic images is also, for other reasons, very demanding. The difficulty does not reside in competition but in evolution. The dialog that these images should support between themselves and their user implies a constant clarity of the image despite frequent changes. Visual ordering, by making the image semantic structure visually explicit will contribute to that clarity.

As stated in the previous section, the purpose of visual ordering in dynamic maps will be to help the user to immediately identify the different components of the image, i.e., foreground, context and background. Several perceptual levels will have to be created in the image. The groups of objects in the same categories will be given the same level of salience by adjusting some of their graphic attributes in the same way. As a simple example, the objects included in the background could all be given a lower brightness. With such a similarity, they would be perceived to be in the same category, providing that this range of brightness would be given only to background objects. A background perceptual level would be created by the simple fact of reserving a certain range of brightness for a given group of objects. Brightness is not the only visual variable that can be used to perform such a task. In this work, it will be shown how color, with its three components, can be put to use to achieve visual ordering.

Delicate problems have to be solved to create perceptual levels that will help the dialog we described earlier. The viewer needs to quickly recognize that some objects belong to a given level. But also, the user needs to make visual comparisons between objects at the same level as well as comparisons between objects at that level and objects at other levels. As an example of such a situation, the forest fire monitoring display might be considered again. At a given instant of the interaction, the icons representing the fires and the icons representing the water supply might be part of the same level, the foreground. The user will need to make visual assessment within this level: Which fires are the most active? - Near which water supply is this fire located? - What is the capacity of this water supply? Also the user may need to make visual assessment between the foreground level and the context level: What are the built-up areas in close proximity to this active fire? - On which road is this water supply located? (This assumes that, at this instant, build up area and road systems are represented at the context level).

Adjusting the visual levels in the image, i.e., establishing the correct visual ordering, to make these multi-leveled visual assessments possible requires a delicate control of the display's visual variables, in real time. For example, an optimal perceptual distance between levels has to be determined . If the distance between levels is too narrow, confusion between levels will occur. If it is too wide, it can be foreseen that visual comparisons across levels will be difficult; if the amount of contrast between levels is too wide, the contrasts between objects within a level become difficult to perceive and visual comparisons across levels are hampered. This optimal distance may vary with the different visual situation offered by the evolving display. The method of color management that is proposed offers a framework within which a delicate control of color relationships will help create the visual levels that will structure the dynamic image.

Global approach to graphic quality maintenance

In a dynamic visual environment, the clarity of the communication is not only dependent on a semantically well structured image. All the elements of the image should be discernible at all time and their appearance should vary only for semantic reasons. It has been stated above that these basic features will be offered by dynamic images only if a deliberate effort is made to implement them.

Losses in discernibility occur when variations in the location or the color of graphic objects cause them to appear too close to the color of their underlying background or the neighboring objects. An objects can be perfectly discernible in one region of the background but can recede into it when moved into another region. This receding is the consequence of the change in location and not of a deliberate semantic operation like changing the object from foreground to context level. Such a confusing effect is due to a lack of planning in the usage of color value in the image. It occurs when the color assigned to graphic objects and the colors used in the background are allowed to be similar. This lack of planning has the effect of limiting the possibilities of information expression in dynamic images. To counterbalance such a misuse of color, most of color variations must be devoted to discernibility maintenance instead of being used for semantic visual operations.

Losses in the constancy of the object's color appearance are also the consequence of changes in the object's locations but also of the object's colors. But the determining factor here is the variation of color caused by simultaneous contrast effects. A color is never perceived in isolation. It is a well known fact that our perception of a color is affected by the colors that surround it. In fact, an absolute appearance for a given physical color (for instance, the color produced on a CRT screen by a given RGB triplet) does not exist. The appearance of a given physical color can only be relative, and will change each time its surroundings are changed [Albers, 1972]. The management of color usage in dynamic mapping has to be designed in view of this inevitable phenomenon. When color is used as a visual variable to express information, variation of its appearance caused by simultaneous contrast effects can be sources of confusion. An object perceived as bright in a darker environment will be perceived darker in a lighter one. A blue object will be perceived purple-ish on a green background and greenish in a red background. These uncontrolled variations are liable to interfere with the establishing of visual levels as well as the usage of color to perform tasks of association or selection.

The problems of discernibility and appearance constancy maintenance can be addressed with two radically different but complementary approaches. The problems can be solved when and where they occur in the display, a local approach, or the likelihood of their occurrence can be reduced by an efficient management of color, a global approach. As stated in the introduction, this work concentrates on the global approach. With the local approach, graphic objects are treated like individual, autonomous agents. The means of detecting graphic conflicts provoked by a new situation are given to them as well as the means of reacting appropriately to these conflicts. For instance, in the work of Ishizaki, simple icons are able to adjust their color for appearance constancy by performing an analysis of their immediate surroundings at their new location [Ishizaki, 1991]. This approach makes an interesting use of the possibilities of real time computing but cannot be the only strategy used to maintain discernibility and appearance simple icons are able to adjust their color for appearance constancy by performing an analysis of their immediate surroundings at their new location [Ishizaki, 1991]. This approach makes an interesting use of the possibilities of real time computing but cannot be the only strategy used to maintain discernibility and appearance consistency in the image. Resolving graphic conflicts by acting locally in many locations in the image might become computationally expensive and might result in a lot of unnecessary conflict detection work. It assumes that graphic objects in the dynamic image must be these rugged entities able to adapt to any bad visual situation. Relying on a local approach only would be overseeing the fact that, at the global level, the visual variables of the image can be controlled to avoid most of the conflicting situations. The two approach can be seen as complementary.

The global management of color use can provide a framework for color variations where graphic conflicts are potentially rare, and the local approach can provide adjustment when graphic conflicts cannot be avoided.

The global approach to discernibility and appearance constancy maintenance is closely related to the establishing of perceptual levels in the image. Discernibility and constancy can be maintained as a consequence of the presence of perceptual levels in the image. It is possible if the distribution of contrast across the perceptual levels is such that graphic conflicts between objects at different levels do not occur. As an example, the interactions between a topographical background and a group of icons displayed over it can be considered. The topographical background is displayed within a range of contrast that will put a lot of its features at the same brightness level used for the icons **(figure 6)**.

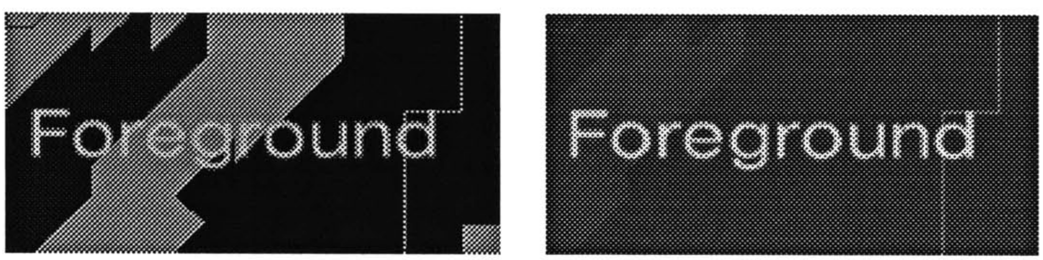

Figure 6. Graphic conflicts are prevented by a good contrast distribution

Conflicts will occur when icons are moved close to or above these features. Such a situation amounts to a misuse of the range of brightness available to the image. By comparing the two parts of **figure 6**, it can be seen that the topographical features of the background can be visually expressed by using a much narrower range of contrast. In the right side image, these background features can be clearly seen by the viewer but do not compete with the text label. Precisely, the contrast between the background features does not compete with the contrast between the icon and the background features. In the right side image, the contrast distribution created two distinct visual levels. The icons can be easily visually parsed into a visual level distinct from the background. Icons can be moved across the background without suffering visual competition from the background features. It is easy to see how this simple example can be extended to an image with more perceptual levels. The example of **figure 6** shows that the discernibility of the graphic objects is maintained as a direct consequence of the brightness distribution in the image; no background location has a level of brightness close to the brightness of the icons.

The appearance constancy of the graphic objects is maintained for less obvious reasons. The contrast distribution makes the color variations caused by simultaneous contrast effects negligible compared to the color variations used in the image for semantic operations. The magnitude of simultaneous contrast effect increases with the perceptual distance between the two colors influencing each other. If an icon is moved across a background that contains areas differentiated by a lot of contrast, the appearance of the icon's color will change a lot each time the icon passes from one area to the other. If the contrast in the background is kept to the optimal level, the minimum level where features can be perceived easily, the contrast between areas will be much lower. As a consequence, the changes in appearance of the icon's color will be much smaller (**figure 7**). If the color variations and the color contrasts used in the image to perform semantic operations are comparatively bigger, simultaneous contrast aberrations can become negligible. The relative relationship between color variations due to simultaneous contrast effects and the color variations due to semantic operations in the system is one of the guiding criteria for the control of the distribution of contrast in the image.

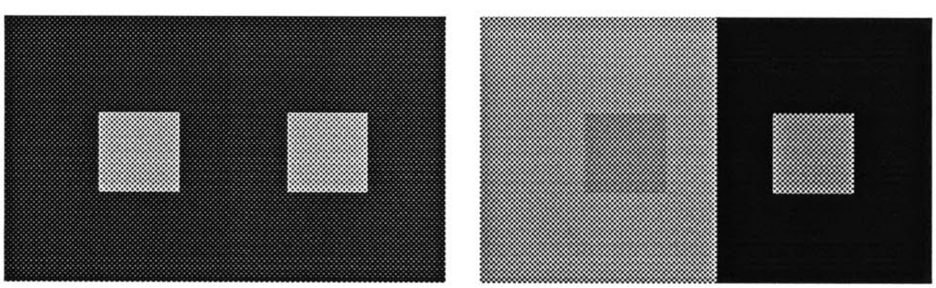

Figure 7. Constancy of color appearance is also helped by a lower contrast in the background.

Perceptual levels are key to efficient dynamic images

The establishing of appropriate perceptual levels in the dynamic image will help achieve two of the three main graphic design requirements presented above, i.e., visual ordering and maintenance of objects discernibility and appearance constancy. These two requirements have to be achieved first since they both contribute to supplying a basic, well designed visual environment for the dynamic presentation of information. The requirement of rapid information extraction which is related to information visual encoding methods will be achievable only in such a controlled visual framework. In this thesis, the research work concentrates on the means of creating perceptual levels that support the dynamic presentation of information.

The purpose of the proposed method of color management is to allow color, as a visual variable with three degrees of freedom, to be used for the creation of these perceptual levels, in addition to its traditional role in conveying association and selection. The requirements of an automatic color management module will be determined in view of this specific purpose.

From the requirements described in the previous sections can be deduced the principles that will determine the characteristics of the appropriate perceptual levels. Within one level the amount of allowed contrast should be the minimum necessary to visually differentiate between the objects belonging to that same level.

The perceptual distance between levels should be wide enough that clearly distinct levels are obtained and that no inter-level conflicts are possible. But to be optimal, it should be narrow enough to allow inter-level visual comparison. Finally, to prevent confusion due to simultaneous contrast aberration, the magnitude of color variations used for semantic operations must be such that color variations due to simultaneous contrast become negligible These principles are interrelated and it will be shown further in this work that they are at the basis of the visual knowledge that has to be acquired to build efficient dynamic mapping environments.

Chapter 3. Color in dynamic mapping

"Je suis contre la couleur qui camoufle l'incompétence et je reste contre tant que l'on croira qu'elle suffit pour representer un ordre..."

Jacques Bertin, La Graphique et le Traitement Graphique de l'Information.

1. The teaching of recent color research

Potentials

Color is becoming increasingly available in the electronic visual environment. As a consequence, the research community is turning its attention more than ever on the elaboration of sound principles for the effective use of color in electronic displays. In view of the literature, it appears that all researchers agree that few principles of good color use are available to the display designer. Also, in view of the current use of color in interfaces and visual applications, it can be seen that a misuse of color can have disastrous effects. The confusion and the strain that can result from the misuse defeats the purpose of adding color of the interface in the first place, which is to bring more speed, clarity and safety. Nevertheless, all researchers, to different extents, agree on the existence of the potential of color as an important visual variable for the representation of information.

In this work, it is believed that color holds an important potential as a major visual variable for in dynamic mapping. Several established facts are at the basis of this potential. They are related to the properties of human color perception.

• The human visual system is capable of performing *parallel search* of color targets in a display [Cowan, 1988] [Davidoff, 1991]. The experimenters asked subjects to find a targets of a given color in an image, among other colored, distracting objects. The experiments showed that subjects were able to find the targets very rapidly, without needing to scan the image. In other words, the human visual system is able to process the color information contained in the field of vision without addressing every part of the display in sequence (**figure 8**). For other visual variable like shape, more attention from the subjects therefore more time is required to perform the search.

• Tasks of identification using color stimuli can be completed by subjects with levels of performances as good as for achromatic visual stimuli like shape [Christ, 1975]. Comparative experiments were performed, where subjects were asked to identify targets in visual displays. Target were differentiated either by shape, alphanumeric symbols or color. In these experiments, color yielded always similar or better accuracy of identification than shape. Alphanumeric symbols would yield better results in some cases but for most of the cases, performance were similar to color.

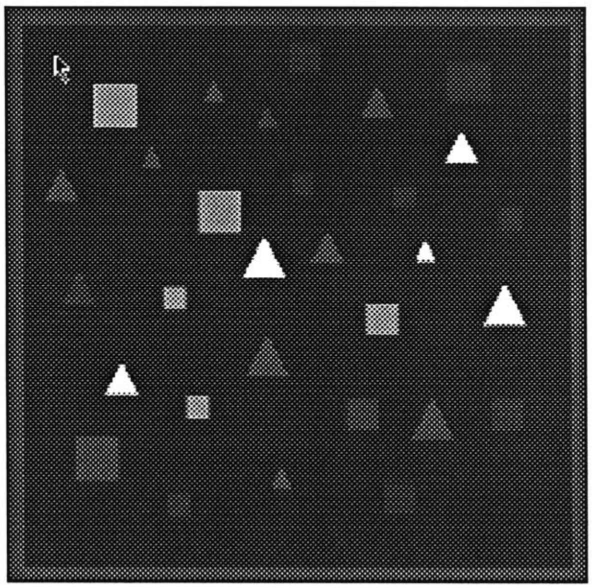

Figure 8. Find the red icons

• The same series of experiments presented by Christ also established that performance with color is independent of image complexity. When the complexity of the image presented to the subjects increased, the efficiency of the achromatic variables (shape, alphanumeric symbols) decreased when the efficiency of color remained constant. Also, color as a redundant variable (when used in correlation with an achromatic variable) was proven to significantly raise the level of performance.

• Color has been proven to convey grouping of objects within displays [Cowan, 1988]. In an image containing many graphic objects, the objects that have the same color will be perceived by the subject simultaneously. This is a consequence of the ability of our visual system to perform parallel search of color stimuli. It therefore, cognitively easy for a subject to recognize the objects of a same color as belonging to the same group.

These facts can be related to the design requirements for dynamic mapping environments proposed in the previous chapter. The ability of the human visual system to perform parallel search of the visual field for color stimuli is a feature that is crucial to dynamic images. With parallel search, complex displays of the kind described in the forest fire example become plausible. In such a visual environment a viewer has to be able to accurately perceive different groups of objects or single objects among numerous distracters. Parallel search indicates that this is a demand that can be safely made. Also, parallel search brings plausibility to the requirement of rapid information retrieval. Parallel search alleviates or greatly reduces the need for a visual scan of the display, thus participating to the speed of information retrieval.

The fact that the performance of color as an identifying variable is independent of the image complexity is also a crucial feature. In dynamic mapping, the display evolves with the unfolding of a problem solving process, and its complexity may greatly vary through the course of a session. It appears that color is a visual variable very appropriate for that kind of display. On its own or combined with shape or other achromatic variable (as a redundant variable [Christ, 1985]), it has the potential to maintain constant the level of efficiency in the display despite variations in its complexity.

In this work, it is believed that these features of the human processing of color information give to color a special status as a visual variable for information presentation. It will be seen further that, despite its limitations for supporting semantic tasks, color will be able to play a structural role in the dynamic image. To the features of parallel search and independence of image complexity must be added the fact that color is the basic component of the electronic image (pixels illumination is specified in terms of color values). This combination enables color to play a major role in the structuring of the dynamic image. It can contribute to the building of a safe visual framework, where achromatic visual variables, along with color, will be used to perform many semantic operations.

Warnings

Two opposite attitudes can be seen in the research community toward the evaluation of the usability of color as a visual variable to present information. The first attitude is conservative and recommends that color should be involved in a limited number of tasks, using the few established principles available. The second attitude tends to see color in the electronic medium as able to achieve more than in the traditional media, and seek to bring out that potential. In this research, the second attitude is adopted. It is believed that the conditions of color availability and controllability offered by high resolution electronic displays are unprecedented and that some risks have to be taken, at the research level, to make full use of the new possibilities. Nevertheless, the warnings given by the research community cannot be lost from sight and are presented here.

Cowan, in his article "Colour Psychophysics and Display Technology: Avoiding the Wrong Answers and Finding the Right Questions" [Cowan, 1988], very usefully summarizes the misunderstandings and ambiguities that appear when display designers look toward psychophysics for guidance in color usage.

A misunderstanding that seems to be frequent in display design is to rely on facts established through psychophysical experimentation to make design decisions about color. Cowan points out that, most of the time, nothing guarantees that the validity of the result can be generalized beyond the experimental visual conditions within which they were obtained. In devising their experiments, psychophysicist create very specific visual conditions in order to isolate variables and make their study possible. Most of the time, the experimental visual conditions are too simplified to be comparable to the visual environments that display designers have to build. Cowan gives strong warnings against these easy generalizations. He suggests that more experimentation has to be conducted that takes into account the real visual conditions of the task to be studied.

This tendency in the field of display design to carelessly generalize experimental results can be explained in part by the scarcity of established principles of color usage in electronic displays. Display designers have to rely for the most part on a limited set of rules of thumb. Cowan accepts that these rules have a limited effectiveness. He warns that no psychophysical experimentation come in their support, and as a consequence, they are not quantitative, which greatly limits the extent of their usage.

The clairvoyant review of Cowan brings to light the need for more psychophysical research to provide display designers with the means to use the full potential of the new possibilities of color in the electronic medium. His concluding statement defines a research agenda that goes toward this goal. "Understanding the psychophysical basis for these rules, and the process of making them quantitative, is the largest question facing psychophysicists in the human factors community" [Cowan, 1988].

Warnings come also from the field of information presentation design. Bertin made a thorough study of the relative competence of the different visual variables in achieving semantic tasks. He gives precise guidelines for the usage of color in expressing information. He shows that in information presentation design it is usual to make too strong a demand on color or to misunderstand its possibilities. He warns that the different characteristics of the three dimensions of color, hue, saturation, value, have to be clearly understood to make an efficient use of this variable. For instance, the fact that at equal saturation, colors of different hues have different values, and conversely the fact that equiluminant colors have different saturation, have harmful consequences on the ability of color to express order or quantity Even though perceptually consistent color models, like Munsell's, are based on this understanding, many users of color are still unaware of its implications in information design. In his classification of the visual variables available for information expression, Bertin proposes a limited role for color. Only tasks related to association and selection can be performed safely with color.

By "association", Bertin means that a color can be associated to a given entity, the color then represent this entity in the display. The viewer can efficiently find and identify an objects by its color or a group of objects by the objects similar color. Selection is the corollary of association, i.e., viewer can efficiently differentiate objects if they have different color. In Bertin's view, this limited competence attributed to color insures that the tasks that are assigned to it make the best use of the characteristics of human color perception.

As stated above, the attitude taken in this research toward the competence of color as a major visual variable is not conservative. Nevertheless, it will be seen further that the limited competence of color for semantic tasks is accepted. It is with tasks related to visual ordering and graphic quality maintenance that the author is willing to take risks. The main goal of this research is to demonstrate that, with an appropriate management method, color is able to play a structural role in the dynamic map (visual ordering and graphic quality maintenance) *concurrently* with a limited involvement in semantic tasks.

2. Graphic design opportunities of color in the electronic medium

The graphic design experience

In the recent years, the computer became an image machine. The new ability of the computer to support sophisticated visual communication set the community of human factor research on a collision course with the field of graphic design. Human factor experts have been rarely involved with print or video media. Conversely, as long as the electronic visual environment offered only textual interfaces with a limited amount of color, graphic designers were not asked to participate to the design of the electronic image. Currently, state of the art computer graphics can support complex images where purely ergonomic issues are woven with problems of visual communication. The visual design problem that have to be solved go far beyond the selection of a correct set of color for a multiple-window interface. As a consequence, graphic designer and human factor experts find themselves addressing the same kind of problems, but their attitudes are very different.

Human factor research tends to study tasks in isolation, in very carefully designed experiments. Many subjects are submitted to the experiments, and the results obtained can be interpreted with statistical methods. The facts that are uncovered have the reliability that such a sound process give them, but as it was mentioned in the previous section, the visual conditions in which the experiments are performed are too simplified. The results cannot be directly adapted to the complex visual situations encountered in visual communication.

The experience of graphic design supplies the mans of orchestrating complex visual situations. In the field of graphic design, images are composed, with multiple elements, to achieve a given communication goal. The knowledge that is used doesn't concern the behavior of an isolated stimuli in performing a given task, but the relationship between several concurrent stimuli. In becoming an expert in his field, the graphic designer builds an experience in managing the visual variables in an image. In doing so, he is used to address both semantic and ergonomic issues. A well designed image or a well design publication presents this necessary articulation between semantic and ergonomic aspects. Information is communicated easily because a good solution to the ergonomic problems allows a message to be parsed effortlessly; ideally, the parsing process is not noticed by the viewer.

Another aspect of the design experience that can help the many display design projects to come is the ability of graphic designer to adapt their principles to the different visual media they have to use. A daily newspaper, printed everyday, in one color, on newsprint, is radically different from a corporate annual report, printed in six color on luxury offset paper (extremes are considered for the sake of arguments). Yet the designer is able to grasp the differences in both the "human interface" aspects and the technical aspects. In both cases, the designer is able to bring the most out of the human and visual characteristics of each medium. Medium-independent principles are applied and medium-dependent principles are developed. From the standpoint of graphic design, the electronic display is yet another visual medium with its human and technical aspects. Medium-independent graphic design principles are still valid (an example is the need for visual ordering in the image), medium-dependent principles have to be developed, for example the need for a method of management of the infinite source of color that is available.

The human factors community is admitting the lack of established principles for color use at the electronic visual interface. It is also asserted that the rules of thumb that are used currently are backed by graphic design principles and a superficial understanding of the human perception of color. The principles that can be derived from these rules are qualified as "sketchy" [Cowan, 1988], and a call for sound quantified principles is made. In this research, it is believed that the graphic design experience can make a wider contribution than supplying limited solutions while quantified principles are developed. Useful images can be so complex that this quantification effort may stumble on a combinatorial explosion. Despite the facts that graphic design principles are difficult to quantify and design decision making is hard to automate, the graphic design experience will have to play an important role in the visual design of electronic displays.

Theory of opponent colors and dynamic mapping

The theory of opponent color is one of the few established facts concerning human color perception that can be relied upon by the display designer [Cowan,1988]. A simplified account of the theory would state that the retinal input from the three types of cones is combined into three opponent channel, an achromatic channel through which pure brightness differences are perceived, and two chromatic channels though which differences along red/green and yellow/blue axis are perceived. Achromatic and chromatic channels have different perceptual behavior: The chromatic channels are less responsive to high spatial and temporal frequencies than the achromatic one [Cowan, 1988]. Cowan signals the three rules of thumb that can be derived from these established facts:

• Where detailed shape information is important, indicate it using significant change in luminance (or brightness).

• Hue and saturation will fill in to achromatic edges. These effect is particularly strong in blues and yellows.

• Flicker is most salient for display color that strongly excites the achromatic channel.

These rules of thumb are certainly usable and reliable but more advantages for display design can be obtained from the particularity of the human visual system accounted for by the theory of opponent colors. Where a human factors expert might see isolated abilities and limitations of the human visual system, a graphic designer sees an opportunity for image control.

From the stand point of visual design, the theory of opponent colors has two important consequences:

• The different behavior of achromatic and chromatic channels concerning response to spatial frequencies (boundaries recognition) offer an opportunity for the control of the relative salience of the graphic objects in the image. The salience of the boundary between two colored surfaces can be controlled by varying the color value of both colors. This amounts to controlling the involvement of the achromatic channel in differentiating between the two areas. There exist a continuum between the equiluminance of both colors, i.e., very low salience, and high color value contrast, i.e., high level of salience. Of course, the correlation between the value contrast scale and the salience scale is not established. Nevertheless, this feature of the human visual system, combined with the controllability of color in the electronic environment can be used to establish visual levels in the electronic map and to help perform tasks of graphic quality maintenance.

• The strong differentiation between the perception of the achromatic and chromatic information contained in color supports the ability of humans to perceive color along three quasi independent dimensions, i.e., the value, hue and chroma dimensions of perceptually consistent color models. The achromatic channel accounts for the color value dimension. The two chromatic channels account for the hue dimension. They also account for the chroma dimension with the spectral purity of the color input. This has a very important consequence in the usage of color as a visual variable. A variation along one of the three dimensions of color will be perceived independently from the two other. A dark red that is lightened is still perceived as red. A dark color that varies from a blue hue to a purple hue is still perceived as dark, etc.... As a consequence, it becomes possible to assign different roles in the image to the different dimensions of color. Color becomes a visual

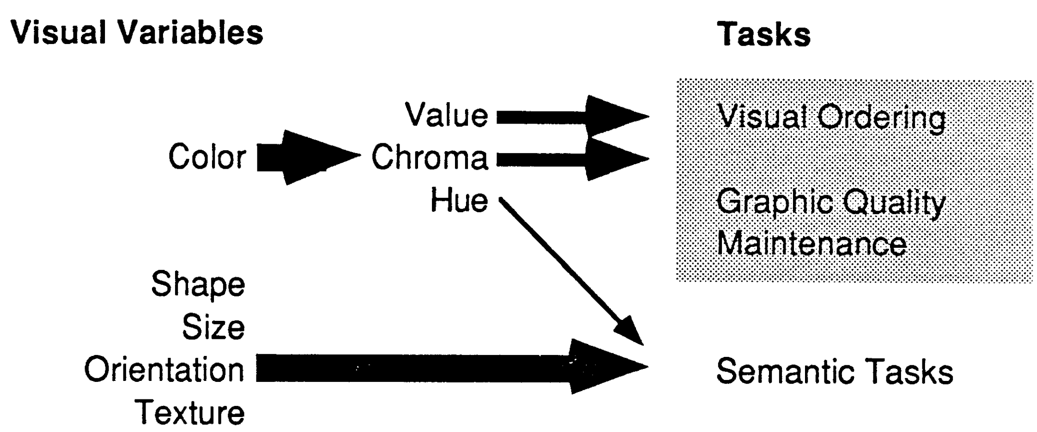

Figure 9. Tasks assignment to the visual variables for dynamic mapping.

variable with three degrees of freedom and supplies the display designer with more opportunity for dynamic image control.

These considerations are at the basis of the design hypothesis that is made in this work. It is hypothesized that visual levels can be established in the dynamic mapping image and graphic quality can be maintained using principally the value and chroma component of color. Further, it is hypothesized that simultaneously, semantic tasks can be performed using principally the hue component **(figure 9)**. The method of color management that is proposed seeks to help create the visual frame work that will make this control possible.

Color in the electronic medium

Two features of color that are specific to the electronic medium are important opportunities for image control in Dynamic Mapping Environments. Color in the electronic medium offers unprecedented availability and controllability.

High resolution CRT displays with 24-bit frame buffers offer to graphic applications a virtually continuous gamut of color covering a wide part of the visible spectrum. Even though it may seem obvious, it is important to point out that at any point of its running time, a graphic application can make use of any color in the gamut. In building images for a computer supported mapping applications, there is no need to carefully pre-select a set of colors, as it is the case in the printing medium. The design effort resides in managing the use of a virtually unlimited source of color. This availability of a wide gamut of color allow the visual designer to think about color choices in terms of dynamics. At any point in time the color of a graphic object can be displaced along the continuum of the three dimensions of color, hue, saturation and value. In the electronic medium, the claim that color can be used in dynamic mapping environments as a visual variable with three degrees of freedom becomes plausible.

The second feature of color that is specific to the electronic medium is its real time controllability. Another seemingly obvious, but important fact, is that color is represented in the computer memory by numbers, i.e., three component vectors in a color space. Color values can be parts of any sort of computations. Software modules can operate on them on these color values that are the basic components of the electronic image. Analysis, comparisons, modification of color values can be performed in real time, which make knowledgeable control of a dynamic map possible.

3.3. The dynamic relationship image/color space

Color relationships and color space

Relationships between colors make a principal contribution to the structure of an image. The design requirements for dynamic mapping that were introduced in chapter 2 can all be described in term of relationships between the colors of the graphic objects in the image. For example, visual ordering will be established by controlling the relative salience of the objects through their colors. Also, discernibility between objects can be achieved by avoiding similarity of color between objects and their background. The control of the color relationships is key to the control of the image. The colors of objects, of groups of objects, will have to be defined relatively to each other and relatively to the full gamut of color available. But, it is difficult to grasp the many color relationships that exist in a complex image and means must be found to simplify this task.

Bender and Jacobson have shown that a lot of simplification and control can be obtained by representing color relationships in terms of color space dimensions [Jacobson, Bender, 1991]. For their color studies, they use the Munsell color model that describe colors with the three dimensions of hue, value and chroma. Every color can be represented within the Munsell color space by a three component vector along these three dimensions. In turn, the relationship between two given colors can be defined by the distance between the two vectors that represent them in the Munsell space. Bender and Jacobson concentrate their study on distances in the hue and the value dimensions. "Alignment" denotes distances in hue, "Amplification" denotes distances in value **(figure 10)**. The visual effect of

Alignment and Amplification is studied in images containing two objects. For example, some text displayed over a background or a foreground pattern displayed over a background. They were able to experiment with different background/foreground color pairs by controlling their relationships through their alignment and amplification in the Munsell color space. Among their interesting results, they demonstrated that when a given relationship of alignment (hue difference) was

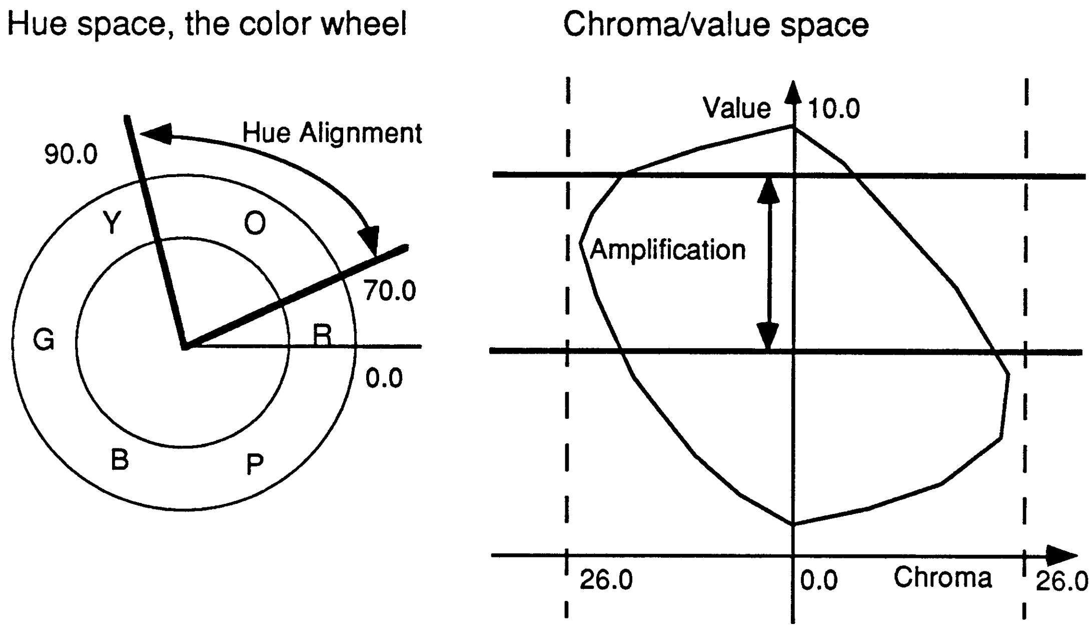

Figure 10. Jacobson and Bender's Alignment and Amplification. Alignment is the angle that separate two color in the hue dimension. Amplification is the interval between two colors in the value dimension.

displaced around the hue wheel, similar response from the subjects were obtained. This means that it is the distance in hue between two colors that seem to determine the response rather that the two particular hue involved. Such a result clearly suggests that the choice color relationships have more significance than the choice of colors taken in isolation.

By defining the color relationships that they study in terms of distances within a color space, Jacobson and Bender elicit the global relationship that exists between a multicolored images and the color space that supports them. Although they have used alignment and amplification to control the relationships between pairs of color, the concept can easily be extended to a multicolored image. The color of every object in the image can be represented by its image vector in the color space. Then the color relationship between one objects and any other can be defined by the distances between their image vectors. It will be shown further how this relationship image/color space can be used as a tool to represent and control all the color relationships in a dynamic image.

Representing the evolving "image color situation"

The relationship between a multicolored image and its underlying color space is a fundamental concept in this work. It will be seen that it is at the basis of the method of color management that is proposed. Using this existing image/color space relationship, the evolving *color situation* of the dynamic image can be represented and controlled.

The term *image color situation* should be defined clearly. It refers to the set of color relationships that is present in an image. It should be thought of as a description of the image in terms of color only, independently from the other visual variables. The diagram in **figure 11** shows how the image/color space relationship gives a representation of the color situation of an image. The color of every object in the image maps into a data point (a three component vector, hue, saturation, value) in the Munsell color space. All the colors in the image can be represented in this manner simultaneously. The result is a constellation of data points in the Munsell color space. This constellation is a representation of the image color situation. It will be referred to as the *color space projection* of the image **(fig 11).**

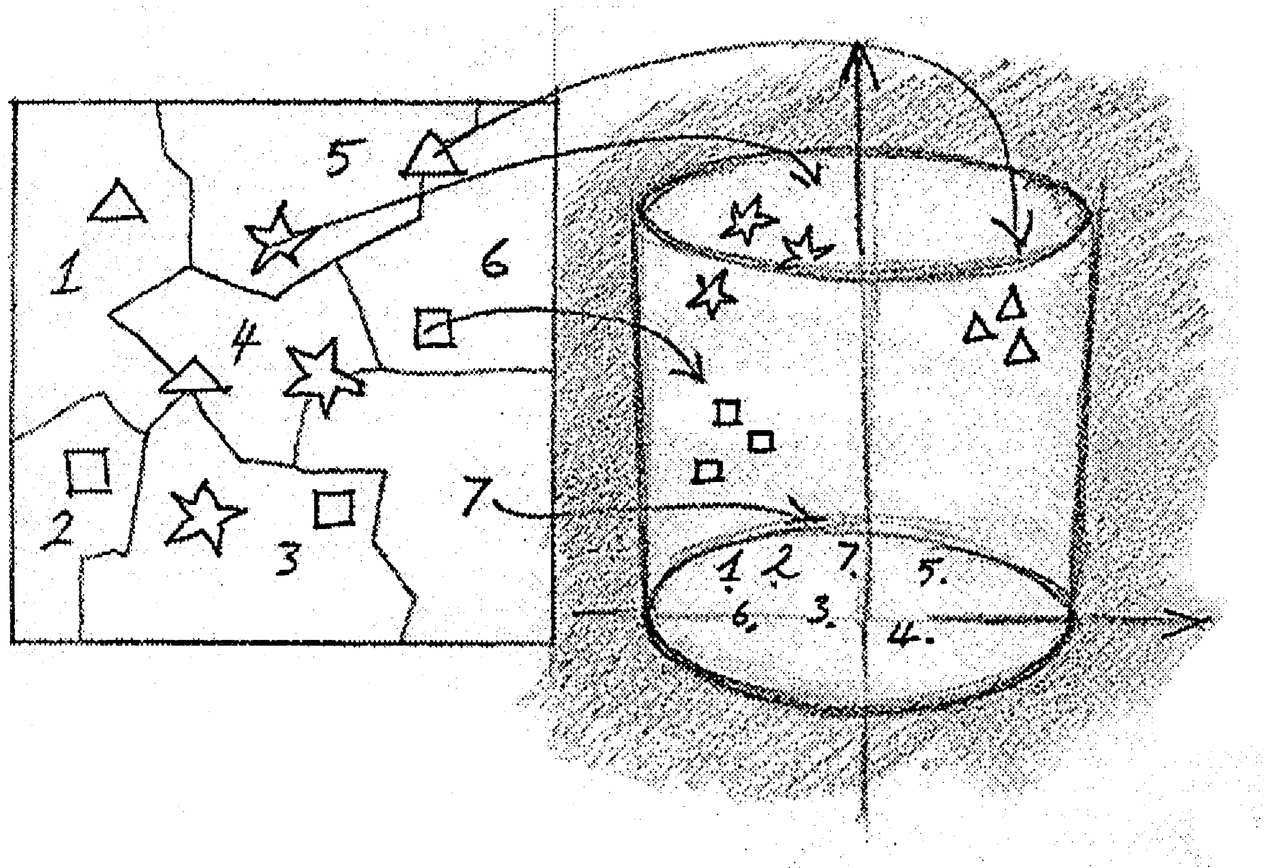

Figure 11. The image/color space relationship, the color of each graphic object maps to a 3-component vector in a perceptually consistent color space

For three main reasons, the color space projection of the image has the potential to help control the evolving color situation in a dynamic mapping image :

- The image color situation is represented independently from the other visual variables, shape, size, texture, orientation.
- A high level view of a complex set of relationships is provided.
- The representation is inherently dynamic.

Representing the color situation of an image independently from the other image components facilitates its analysis and its control. The color space projection can be viewed as extracting the color situation from the image. The advantage of this feature can be understood by considering that a graphic designer is usually able to conceptually isolate the color situation in a design piece, in order to make decisions about it. Similarly, an automated color management module will refer to the image color space projection as a source of information about the color relationships of the image only.

The color situation of a dynamic map can become complex very quickly. With multiple groups of graphic objects present in the image at the same time, the amount of color relationships to be addressed becomes quickly intractable. The color space projection of the image provide a global view of these many relationships. The color situation can be addressed at any level of detail. Clusters of colors are readily discernible as well as the relationships between them. The standing on any object's color as it relate to the other colors in the image can assessed.

The color space projection of the image is a direct mapping of color values into a three dimensional Munsell space. From the stand point of software implementation, the only required operation is the conversion from RGB to Munsell specifications. Every time a new color is added to the image or a color is modified, the its conversion into Munsell specification constitutes its projection into the Munsell space. This representation is inherently dynamic because all modifications of the image are automatically reflected in it. This feature is obviously necessary for a color management module that has to perform a continuous control, in the background, while the mapping image evolves.

Envisioning the color situation of an image independently from the other image components is a concept that has precedents in Graphic Arts and Design. Particularly, the painter and teacher Josef Albers, in his seminal course on color basics at Yale University, described the set of color relationships in an image as a "color constellation". He proposed visual exercises where his students were asked to visualize the color constellation in a given image. The student had to mentally build a representation of the color relationships in the image, and to use it to modify the image in a controlled manner. The concept of color constellation gave the student a global understanding of the color situation in the image, understanding that allowed a deliberate control of the image.

3.4. The Munsell color space

Conformity with the human visual system

Since the relationships that have to be controlled are perceptual, it is important to use a color space that is perceptually consistent. The Munsell space approximates this requirement. It specifies color in terms of, hue, chroma (saturation), and value, dimensions that are intuitive to human subjects (**figure 12**).

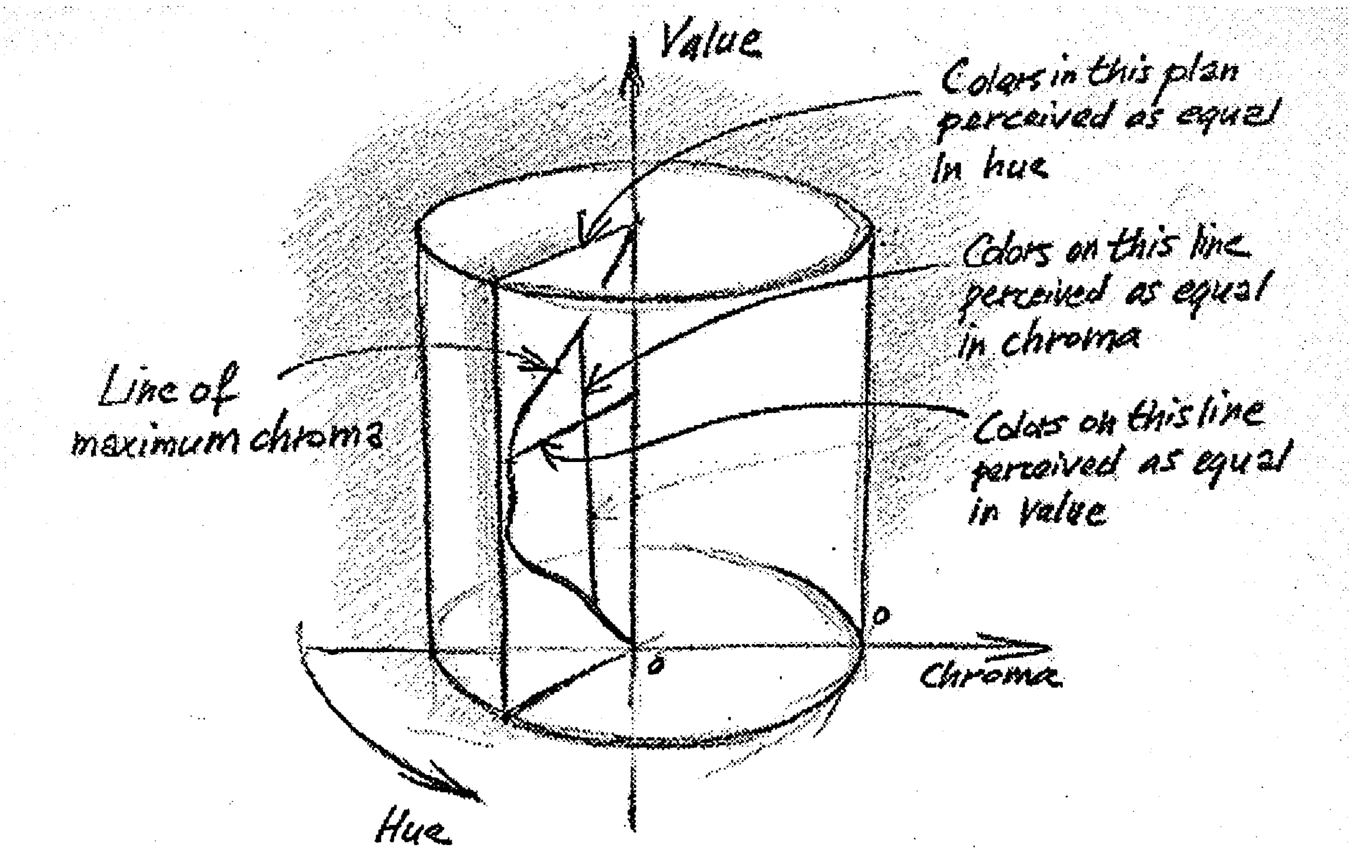

Figure 12. A schematic view of the Munsell color model

By perceptually consistent it is understood that the color variations along the three dimensions of the space must compensate for the non-linearity of the human visual system in perceiving color. The non-linear human visual system perceives an uneven color gradation when submitted a color gradation with a linear progression in its specifications. Compensating for these non-linearity consist of distributing the color samples in the 3-dimensional gamut in a such a way that the human eye will *perceive* linear gradations of color along the three dimensions. Alfred Munsell performed this difficult task at the beginning of the century. He used a large number of human subjects that used their own visual judgment to classified painted color samples according to his requirements. Sets of color equal in value, equal in chroma and equal hue could be derived and ordered into a three dimensional model. The reliability of the Munsell model resides in the fact that it was derived from purely perceptual experiments. A database containing the ordered color samples in CIE specifications is available from the Munsell Color Company. In this work a continuous Munsell color space is used. Most of the RGB specified colors available on a 24-bit color CRT can be converted into this continuous Munsell specification by interpolating between 4 Munsell color samples. The conversion code was developed by Bender in the Electronic Publishing Group at MIT's Media Laboratory.

A color model that offer such perceptual linearity is necessary to allow color modifications with a predictable visual effect. Most color spaces in use in computer graphics (RGB, HSV) do not fulfill, this requirement. The RGB space is inevitable since the colors of the pixels in the frame buffers of graphic workstation are specified in terms of red, green and blue components. It is the fastest space from the standpoint of computation, but there is no visual orthogonality between the three component, i.e., a modification of one component visually affects the two others. The HSV color space (HSV stands for Hue, Saturation and Value) is an improvement over RGB because it is base on the same polar coordinate system as the Munsell space (saturation is equivalent to chroma). HSV offers visual orthogonality between its three components but the color specifications are based on linear mathematics which do not take into account the visual systems non-linearity. As a consequence, a color modification of a given distance is perceived as having a different magnitude in different locations of the space .

Consistent color distribution

The organization of the space must be related to the organization of the human visual system. It is known that the human visual system processes color along two distinct channels: achromatic and chromatic (opponent color theory). A color space has to mirror this structure by keeping the achromatic component of color (lightness contrast) and the chromatic components (hue, saturation) independent. When this requirement is fulfilled, the distribution of color in the space becomes intuitive to the designer and to the user, and meaning can be attached to color variations. The RGB space does not offer this advantage. For instance, if an RGB-specified color is modified by increasing its blue component, the color will usually become *both* lighter and bluer. But if the red and green component of the color are high, then the increase in blue will only cause an increase in lightness to be perceived. This makes it very difficult to make meaningful color modifications using the RGB color space. Within the Munsell color model, a change in the hue dimension reliably effects *only* a change in hue to be perceived, the value and chroma of the color staying constant. The Munsell space offers a quiet reliable orthogonality between the three components, hue, value and chroma.

The Munsell color space as been elected, in this work, as a base for all color manipulations. The main reason for this choice is its availability and its sufficient reliability. Nevertheless, it is important to point out that the Munsell data was gathered through visual experiments performed with painted samples that reflected light. On computer displays, color is formed by radiating colored light, which constitute a visual situation quiet different from the Munsell experimental situation. During this work, discrepancies could be noticed in the linearity of the Munsell color space in the electronic environment (in the blue hues, chroma seems to present non-linearity). Other color models approximate the perceptual linearity requirements in the electronic visual medium. An example is the CIE L*a*b* model. Building a perceptually linear, computationally fast, color model is still an open research problem. **Figure 13** shows a 3-dimensional, color view of the Munsell space. Note the irregular shape that is due to an ordering of colors that compensate for the human visual system non-linearity.

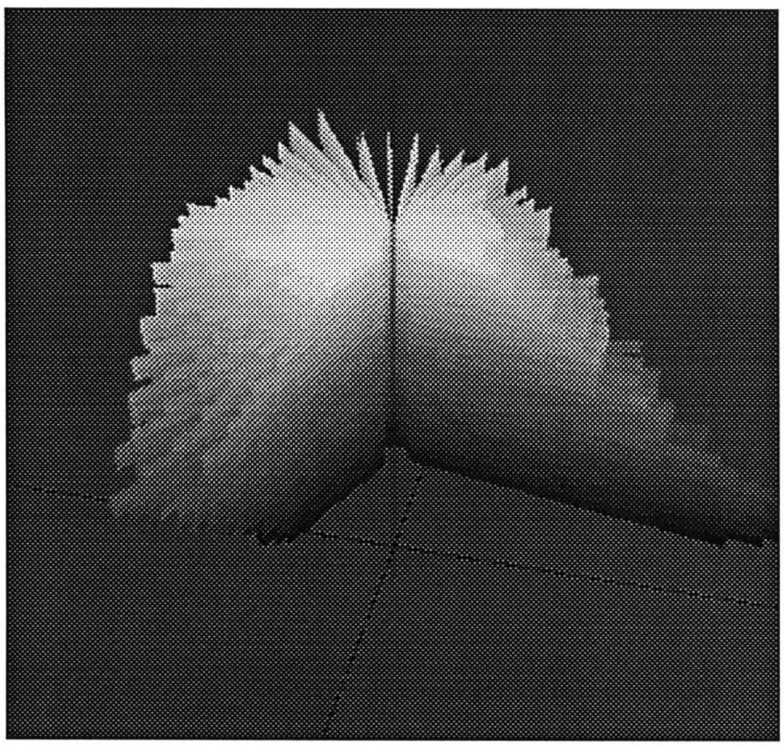

Figure 13. The Munsell color model. Most of the red hues have been cut out to show the internal distribution of colors.

Chapter 4. **The color management method**

1. Overview

As described in the previous chapter, the image/color space relationship is still an amorphous entity. It amounts to a simple mapping of color values in a the three-dimensionnal Munsell color space. To become the infrastructure of a color management method, it has to be organized in a manner relevant to the management task at hand. There is two interrelated purposes for this organization:

• The method has to help the dynamic image to make the best use of the perceptually controlled color resources of the Munsell space.

• The method has to serve the tasks that have been assigned to color in dynamic mapping images, i.e., a heavy involvement in establishing visual ordering and maintaining graphic quality; a reduced involvement in semantic tasks (**figure 9. chapter 3**).

To fulfill these two purposes, the image/color space relationship has to bring together the evolving semantic structure of the mapping image, and the static color configuration of the Munsell space. On the image side of the relationship, the semantic structure is dynamic and characterized by a need for color changes. On the Munsell space side of the relationship, the color configuration is an inherently static entity, it is the relative position of the colors in the space that make them usable in a perceptually consistent way.

This dichotomy between a dynamic image and a static underlying color space is at the origin of the two complementary tools that are used in the method to take advantage of the image/color space relationship.

• The *Color Containers* : They are dynamic entities that can be viewed as vehicles for containing the colors of graphic objects and that are able to move them across the color space in a controlled manner.

•The *Color Zones* : They can be viewed as regions of the Munsell space, signaled by beacons, which main function is to guide the evolution of the color containers in the color space.

With the help of these two complementary entities, an automated color management module can operate on the color situation of the image. The color containers are directly related to the image. Each group of object can have a container assigned to it. The colors assigned to each objects in the group will be defined relatively to the container. Each time the group becomes part of a semantic operation in the image (its role in the image is changed), the color modifications resulting from the evolution can be performed by displacing the container in the color space.

The color zones are directly related to the configuration of colors in the Munsell space. A set of color zones performs a partition of the Munsell color space that defines which regions of the space can be used to achieve a set of given visual effects (for instance, establishing perceptual levels). A color zone encloses a limited region of the color space. The boundaries of the region are defined by the visual characteristics of the colors existing in that region. For instance, a color zone can enclose all the colors with values between 2.0 and 4.0 on the Munsell value scale (0.0 to 10.0). The color found in that zone will be of all possible levels of hue and chroma, but all colors will have low values.

To perform a controlled color modification on a group of objects, the color container assigned to it will be simply displaced from one color zone to another. In the new color zone, the objects will find a new set of colors. These colors will have the visual characteristics that are appropriate for the new role of the group of objects in the image **(fig 14)**.

In the folowing paragraphs, the functionnalities of the colors containers and the color zones will be exposed further. It will be shown how they form a flexible control device for the management of the dynamic image color situation. Combined with the appropriate perceptual knowledge they will form the basic working elements of a color management module.

2. Color containers

Definition

Color containers and color zones, in their simplest definition are sub-volumes of the Munsell color space. They are defined by the six boundaries of the sub-volume along the three dimension of the space. The following is an example of a color container definition **(fig 15)**:

Hue boundaries (0.0 to 100.0): Min Hue = 50.0 Max Hue = 65.0

Chroma boundaries (0.0 to 26.0): Min Chroma = 11.0 Max Chroma = 16.5

Value boundaries (0.0 to 10.0): Min Value = 6. Max Value = 8.0

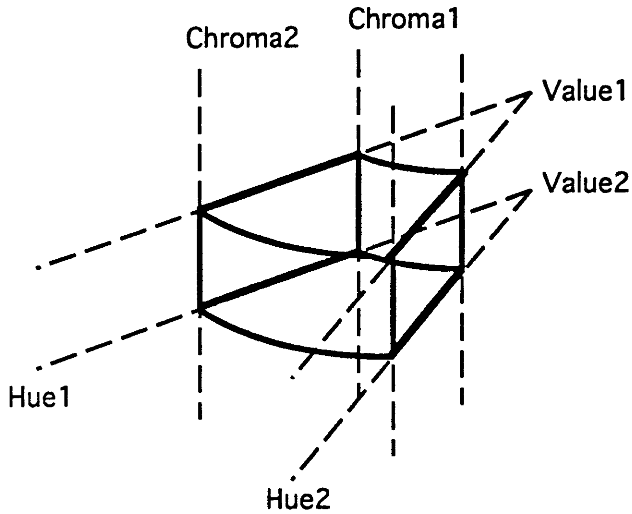

Figure 15. A color range is a sub-volume of the Munsell color space

A sub-volume defines a range in the color space within which single color can be chosen. So far, the definition of color containers and color zones are identical. They will differ by their function in the organization of the image/color space relationship.

The color containers principal function is to hold sets of single color vectors. The colors of the objects in a group are all held by the color container assigned to it. This means that all the colors in the group will be constrained to be located within the color range defined by the container. This relationship between the graphic objects colors and the container will remain true, what ever changes are applied to the location or extent of the container during the evolution of the image.

The implementation of this relationship is very simple. The single colors assigned to the objects are specified relatively to the color range defined by the container. Instead of being specified by an absolute Munsell vector (hue,value,chroma), a vector of values normalized relatively to the range is used **(fig 16)**. The vector is composed of three real number between 0.0 and 1.0, which denotes the position of the single color in the container. This mode of specification will be referred to as *normalized Munsell vector*. By normalizing the specification of the single colors relatively to the boundaries of the container, only the relationship of the color to the container is stored. The final specification of the color is determined by the current location and the extent of the color container. As a direct consequence, all the changes applied to the color container are automatically inherited by the single colors contained in it. This configuration gives the container its ability to carry colors across the color space and to control the relationships between the color it contains. The color containers are, therefore, emminently dynamic entities.

The normalization of color values relatively to ranges of the Munsell space have to be situated in view of the human visual system non-linearities. The perceptual accuracy of the color relationships that can be made with the color containers is dependent on these non-linearities. The Munsell space was devised in an effort to compensate for them and offers an approximation of a perceptually linear color space. The magnitude of the discrepencies that exist in the Munsell space is directly related to the reliability the color modification that will be performed using the color containers. In any case, the margin of reliability has to be compared with the magnitude of the color modifications that the container will have to perform. For the tasks of visual ordering and graphic quality maintenance, the experimentation demonstrates that the color modifications are large enough not to be perceptibly affected by the imperfections of the Munsell space. The determination of thresholds of usability for this method, in view of the tasks that it has to perform, is important, but is not with the scope of this study.

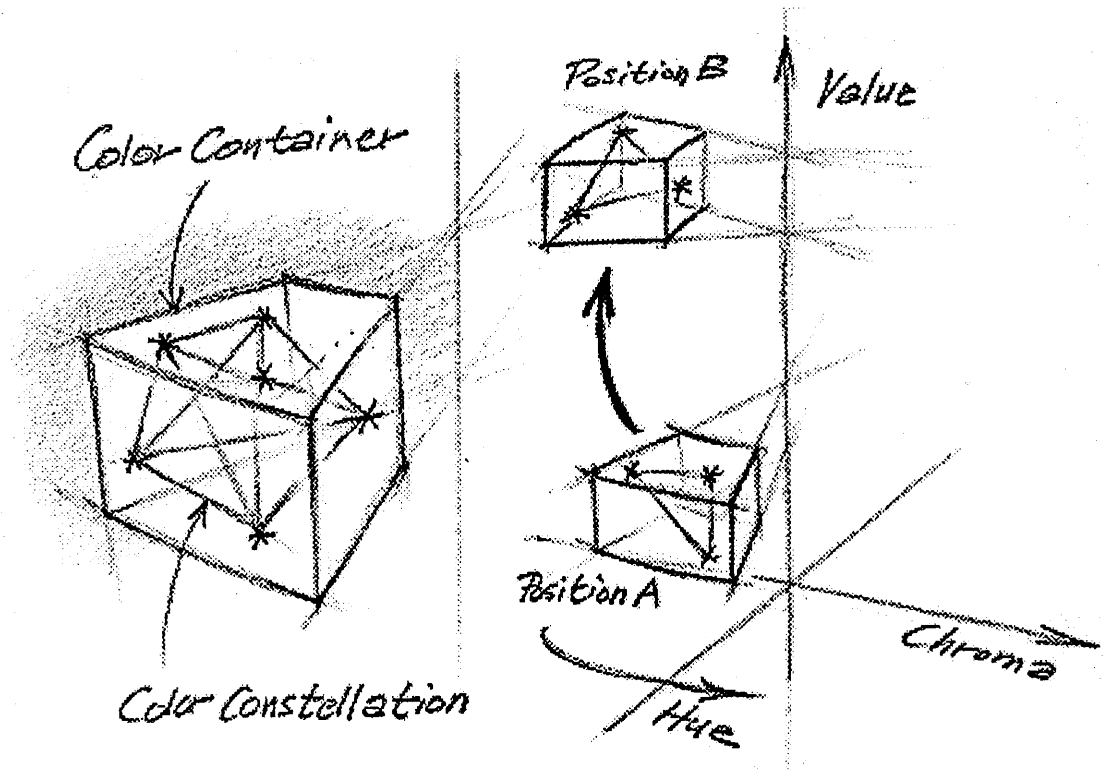

Figure 17. Color constellations are held by containers. Color containers carry constellation across the Munsell space

4.2.2. A vehicle and a controller

The specification of colors relatively to the color range defined by a color container has the important effect to represent the relationships that exist between the all the colors in a container. As it is shown in **figure 17**, the colors held in a container form a constellation of data points that explicits the relationship between these colors. The mode of storage of the individual colors, i.e., the normalized Munsell vectors, allows this constellation to be conserved, despite the changes applied to the location or extent of the container. This feature allows color container to play two roles. They can be the vehicles for displacing the color constellations across the color space, or they can control the appearance of the color constellations.

A color container becomes a vehicle when its location in the color space is changed and its extent in the three dimensions of the space remains the same. In this case, the color constellation is displaced to the new location without undergoing any distortion. The same color modification is applied to all the color in the constellation, and the differences between them remain the same. The visual effect of such a transformation can be observed in the examples presented in **figure 17**. Where ever the container is displaced into the color space, the inter-color relationship is conserved. The lighter objects remain lighter; the hue differences between objects remain the same even if the hues themselves have changed.

The function of color vehicle is very important for the kind of dynamic mapping environments described in the opening example. A large part of the color modifications that will occur will be displacements of groups of colors across the color space. For instance increasing the relative salience of a group of icons can translate into making all these icons lighter by the same amount. This operation can be simply done by translating upward in the color space the container that holds the icon's colors. All the icons will, indeed become lighter, but their respective hues and chromas will remain constant. Providing certain condition, such a visual transformation can be percieved by the user as an increase in salience only. The meaning attached to the hue (for instance, the identity of the objects) will not be lost, since the respective hues of the objects will remain the same.

The color containers play a role of controllers of the color constellation within them, when the extent of the color range they define is modified. The diagram in **figure 18** shows that modifications to the extent of the color range, i.e., displacement of the boundaries of the container, apply a distortion on the color constellation within. The distortion is not random, it is proportional to the modification applied to the container. The color relationships denoted by the color constellation are modified in their amplitude only, not in their configuration. The visual effect of that kind of transformation can be observed in the examples presented in **figure 18**. An increase of a container's extent along one of the dimension of the space results in an increase of the contrast between the colors along that dimension. Conversely, a decrease in extent results in a decrease in contrast.

This function of color relationship controller has a lot of potential for dynamic mapping displays. It brings to the management method the power to conceal or to reveal a color relationship according to the need of the situation. Storing the constellation of objects colors relatively to the color containers embeds a set of color relationships into the container. As the standing of a group of object evolves, the relationship that exist between the objects color can be revealed with different degrees of amplitude. If the group happens to be participating to the

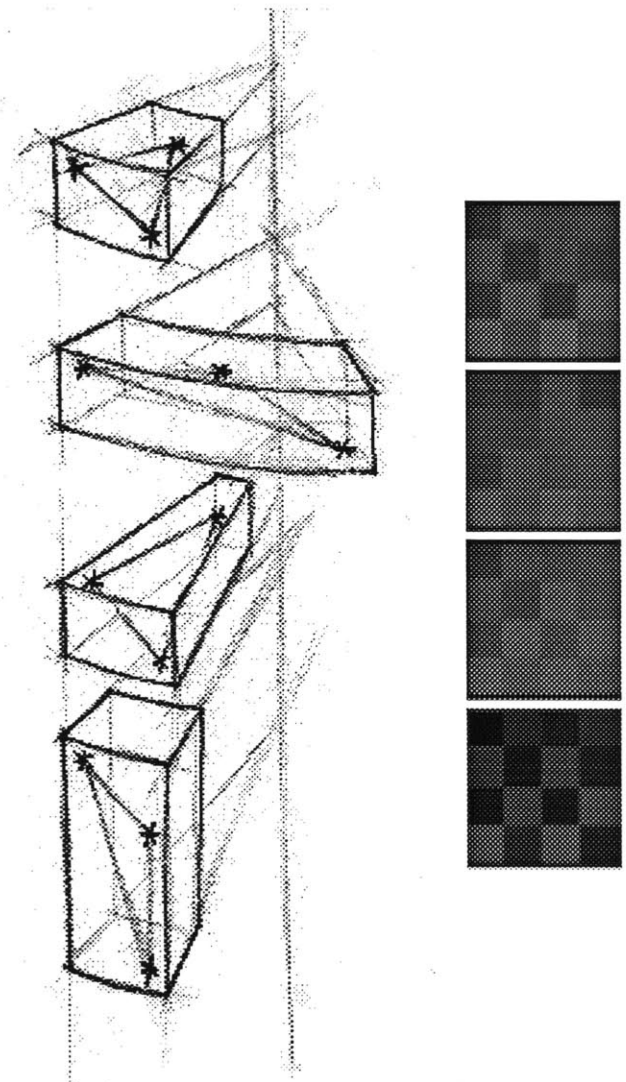

Figure 18. The visual effects of changing the extent of a container.

main focus of interest, the color relationship within it can be expressed to the full amplitude by extending the container to a wide range in the appropriate dimension. Conversely, if the group of objects needs only to be present in the context, the extent of the container can be reduced and the color relationship between the objects will be visually attenuated.

A container's location can be changed and its extent modified simultaneously. In this case containers cumulate the functions of vehicles and color relationship controllers. In an interaction with a dynamic mapping image, this type of visual operation is likely to be frequent. When, at a given instant, a group of object has to be perceived as part of the visual context, its salience should be low and the relatioship between its elements should be concealed, since the group is not part of the main interest. When the group becomes part of the main interest, it has to be moved into a foreground visual level, and the relationship between its elements has to be revealed. This complex visual operation can be achieved whith a displacement of the group's color container combined with an extension of its boundaries. Such an operation results in a simultaneous increase in the salience of the group and in the amplitude of its internal color relationship **(fig 19)**.

Color controllers , as vehicles and controllers of color relationships within groups of objects have the potential to become efficient tools to support the type of interaction that is expected from dynamic mapping environments. The modifications of their locations and extents in the color space have to be guided by sound perceptual knowledge in order to result in controlled visual operations. The color zones will assumes that important function.

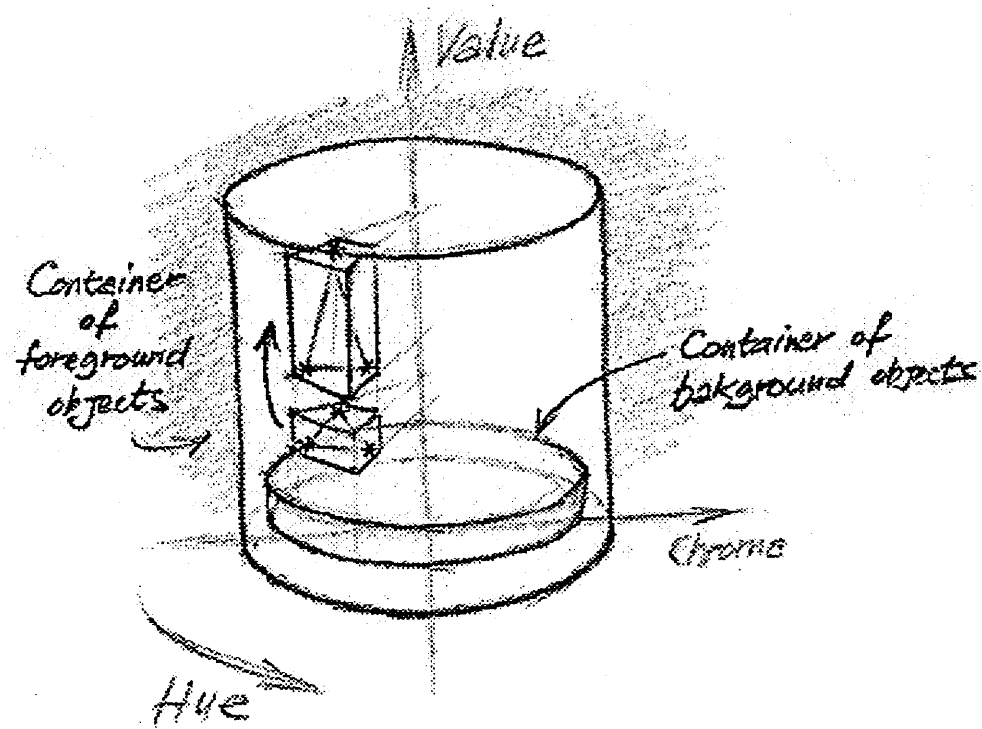

Figure 19. The change in the salience of the foreground objects is obtained by moving the foreground container up in the value scale and by increasing its extent in the same dimension

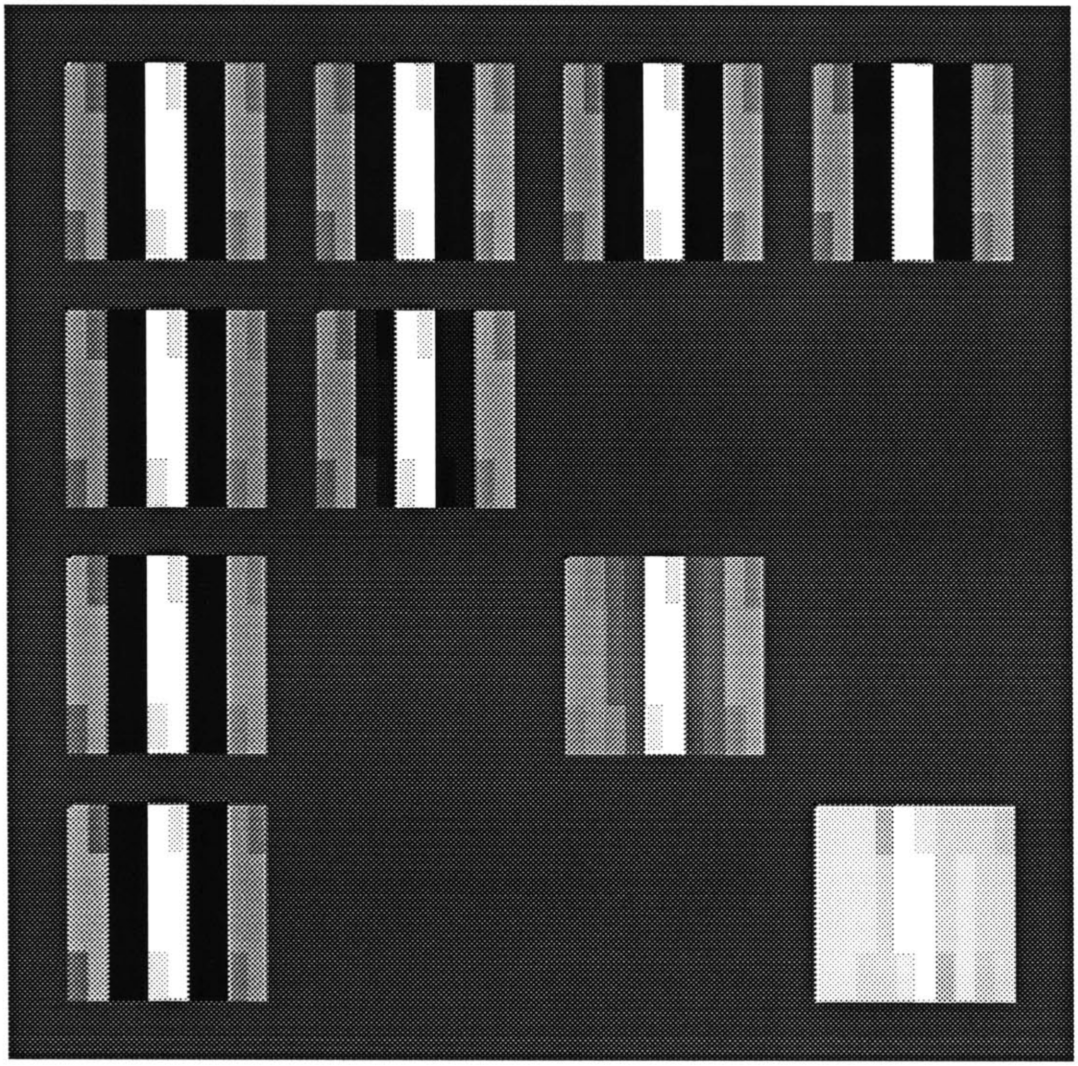

Figure 20. This figure is uderstandable only if displayed in color. Color copies of this thesis can be found at the Visible Language Workshop, Media Laboratory, E15-443.

An icon which color is controllable in real time. Every pixel in this icon is represented as a Munsell normalized vector. This enables it to be displayed using any range of the Munsell space. In the top left example the icon uses the full Munsell space. Along the horizontal axis the range in hue is gradually reduced to a narrow blue range. In the diagonal, the range is reduced to a narrow, high value. In the vertical axis, the range is reduced to a narrow high chroma.

It is important to notice that these images are all different appearance of the same icon, represented by the same data in memory. These variations of appearance can be used to express changes in the entity which the icon is representing in the image. More research has to be conducted to explore the possibilities of this dynamic device.

Color containers and bitmap based images

So far color containers have been associated to group of simple graphic objects. All objects in a group have a single color attached to them, and the container holds the constellation of data points that the group of single colors form in the color space. Color container can be used similarly to hold and control bitmap images. It is easy to imagine that every pixel in a bitmap can be dealt with by the container as a single object with a single color attached to it. A bitmap will form in the color space a constellation of data points that will be more complex but just as much controllable as a group containing a limited number of single colors.

The implementation of bitmap control through color containers is simple. The familiar RGB specified bitmap has to be converted in Munsell specification. Then the value of every pixels has to be normalized relatively to the full range of the Munsell space **(fig 20)**. The data that is obtained by such an operation is a new bitmap format that is an array of normalized Munsell vectors. A color container can be assigned to such a bitmap, and the color constellation formed by the bitmap can be operated on by displacing and modifying the extent of the container. The visual effect of such a transformation can be observed in the examples of **figure 21**. It is important to notice that all this different appearences are obtained from the same data in memory. This is an example of the appropriateness for dynamic visual environments to store color relationships instead of absolute color values. The commitment to a final appearance can be delayed until display time. The data that is stored can be controlled and transformed at will to fit a given semantic situation.

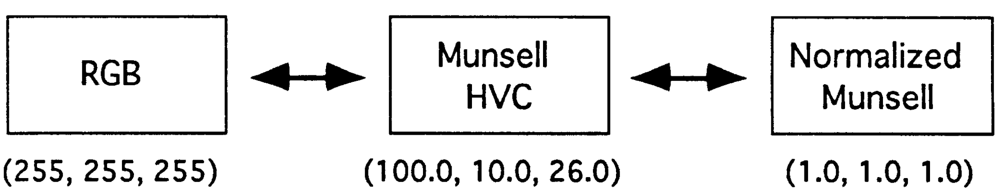

Figure 20. Bitmap format contollable with color containers.

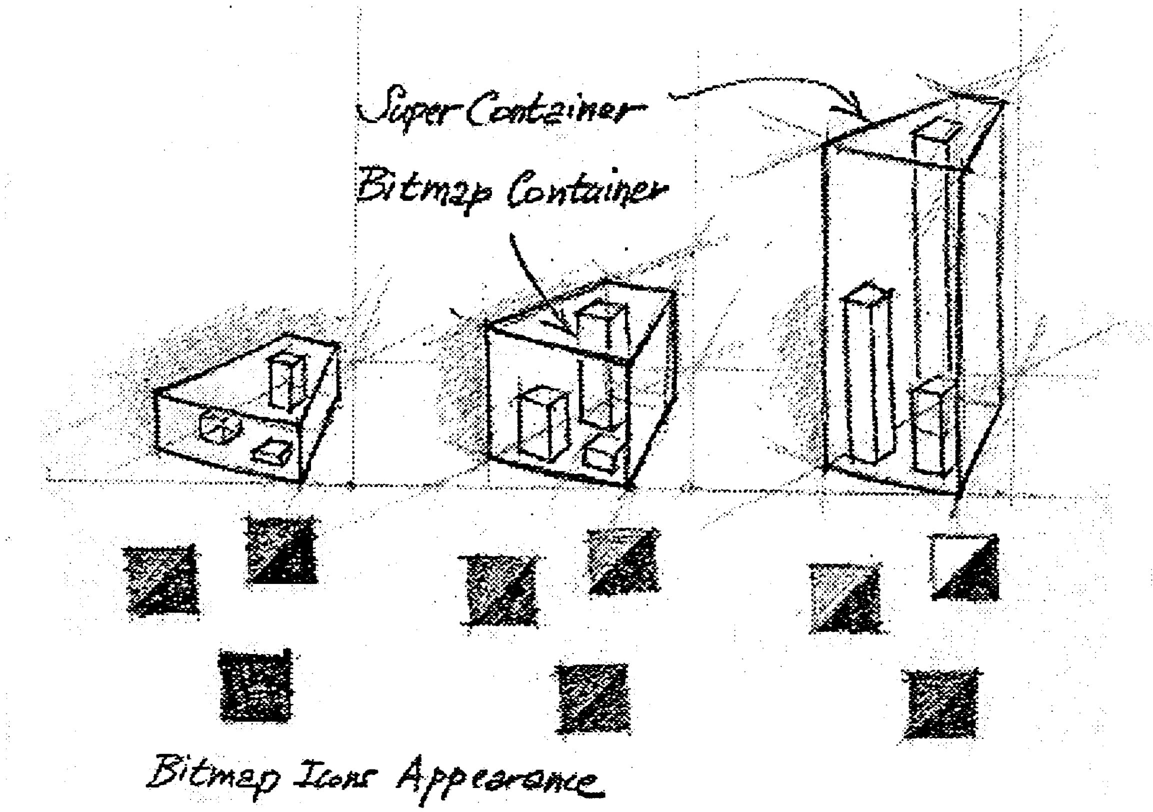

Figure 22. Appearance of icons can be changed by distording their color containers

From the standpoint of dynamic mapping, the control of bitmap appearance has two forseable advantages. The topographical background of a map, to be usefull, needs to be fairly complex and is difficult to build with separated, simple graphic objects. A controllable bitmap is specially appropriate to hold the topographical background information. By controlling the extent of its associated container in the three dimensions of the color space, the topographical features can be given the appropriate level of salience. The background as a whole can be given a paricular relative salience by giving its associated container the appropriate location in the color space.

Controllable bitmaps can also be used to create complex icons. Relevant visual information can be imbedded in small size bitmaps. These bitmap's appearance can be controlled similarly to simple graphic objects. By operating on the extent of their containers they can be made to appear like single objects or the visual information imbeded in them can be revealed (**figure 22**). Such a feature opens interesting possibilities for using icons to perform semantic tasks. The icons

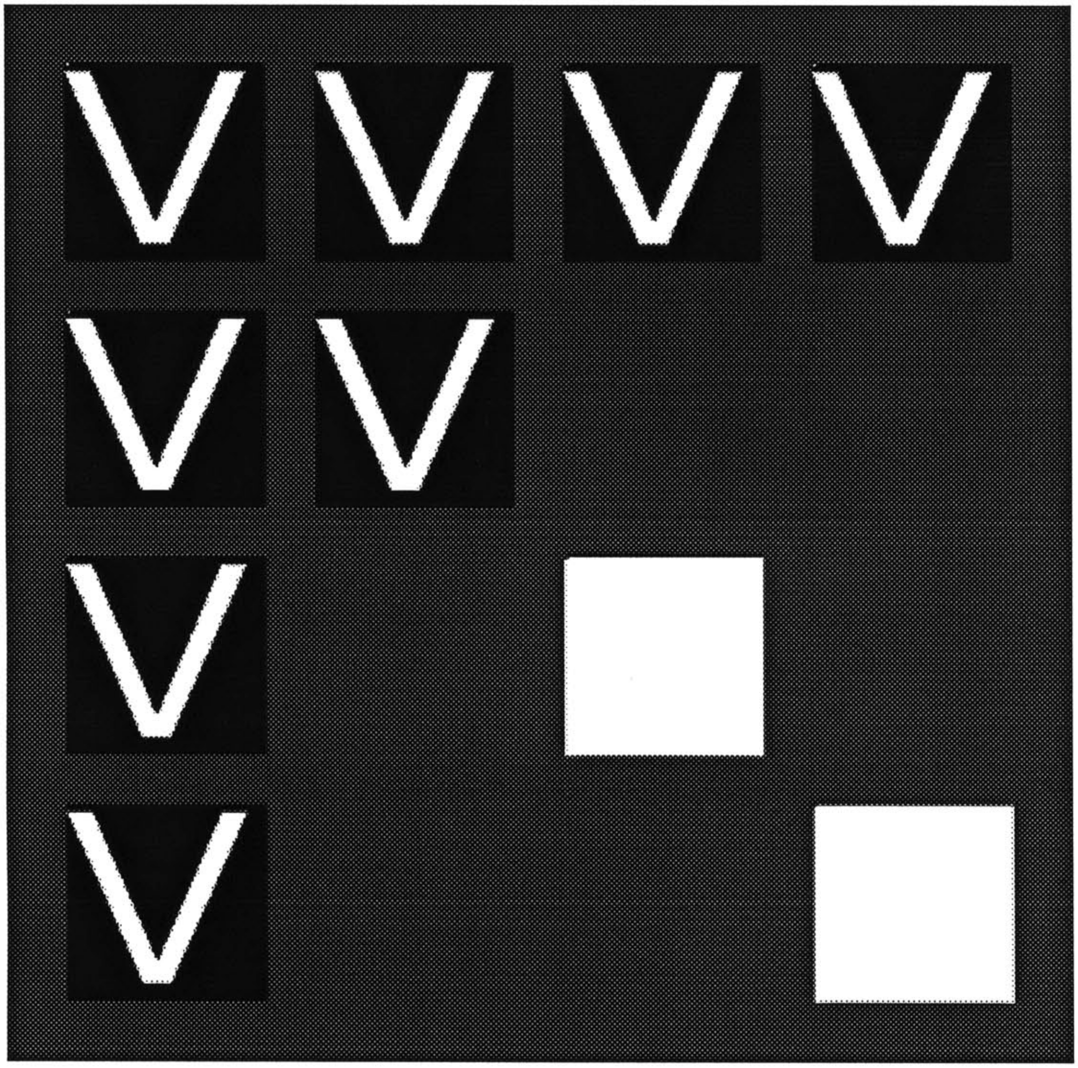

Figure 23. This figure is understandable onlu if displayed in color. Color copies of this thesis can be found at the Visible Language Workshop, Media Laboratory E15-443.

Similarly to figure 20, this icon is represented by a bitmap of Munsell normalized vectors. A different shape has been imbedded in each of the bitmaps three banks, i.e., the hue, value and chroma banks. An H is in the hue bank, a V in the value bank and a C in the chroma bank. This is achieved by giving each pixel a maximum value when it is part of the shape (here a letter) or minimum value when it is part of the background. Using a different shape for each bank, three shapes can be imbedded in the same icon. The three shapes can be revealed of hidden by modifying the color range within which the icon is displayed. Only one shape can be revealed or any combination of the three.

More experiments have to be conducted to evaluate the potential of this device. Different combinations of shapes (overlapping and non-overlapping) and color restrictions have to be explored .

can carry shape within them additionally to their outline shape. Contrast within icons can be used as a visual variable to express quantitative relationships between icons. Finally, it become possible to embeded in the bitmap icon different kinds of visual information along the three dimensions of the color space. This mean that when the extent of the container is increased successively along one of the dimension only, three radicaly different appearance will be obtained. Icons could then have three different visual states that could be used semantically **(figure 23)**.

Carrier of the image semantic structure

Color containers have also the important role of carrying into the color space projection of the image its semantic structure. Every arbitrary group of elements in the image can be assigned a color container. Super containers can hold sets of containers. The assignment of container can be made to reflect the groupings and super groupings of objects in the image. A system of interrelated containers can be created in the color space projection that will reflect the image semantic organization. The diagram in **figure 24** shows an example of a simple image hierarchy reflected into the image color space projection by the layout of the containers. In this case, the group of objects that are semantically related can be given containers enclosed in a super container. As a consequence, semantically related groups can be controlled individually or together as a super group.

This tight relationship between the semantic organization of the image and the organization of the color containers in the color space projection of the image is an important feature of the management method described here. It gives the method the power to operate on the color situation of the image in a manner that's consistant with its semantic structure.

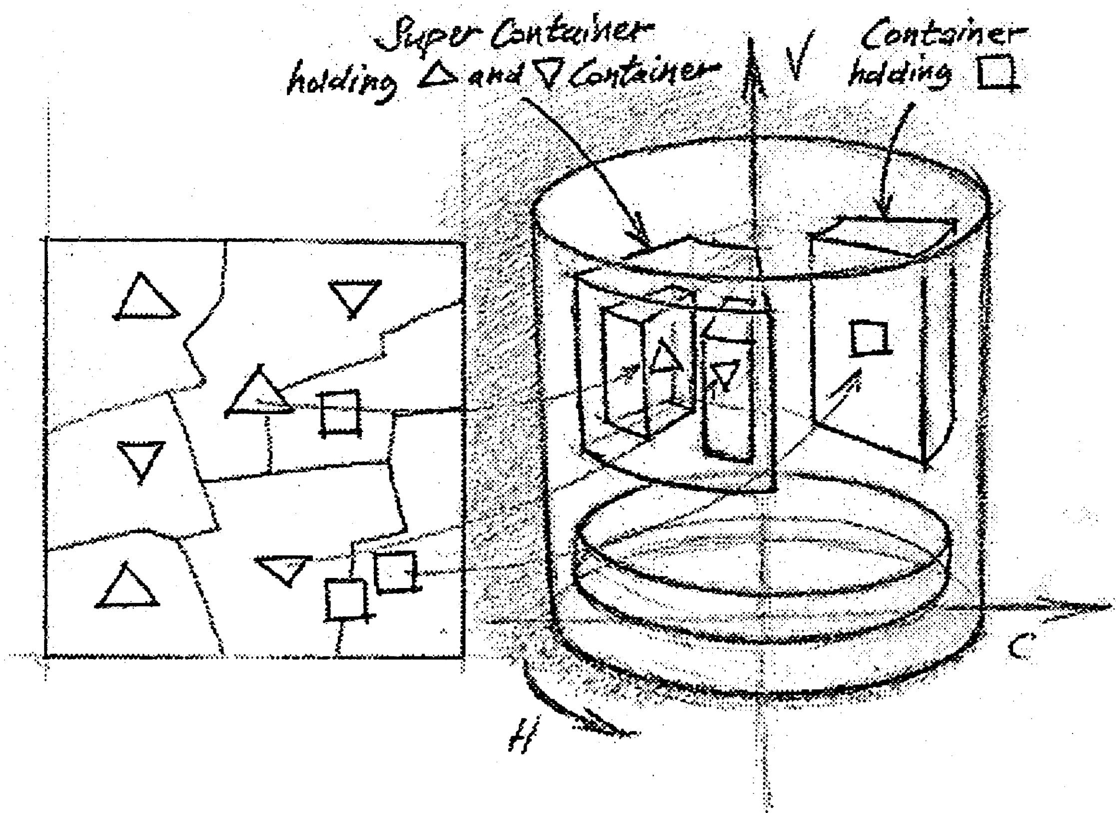

Figure 24. The image's semantic structure is reflected in the color container's structure

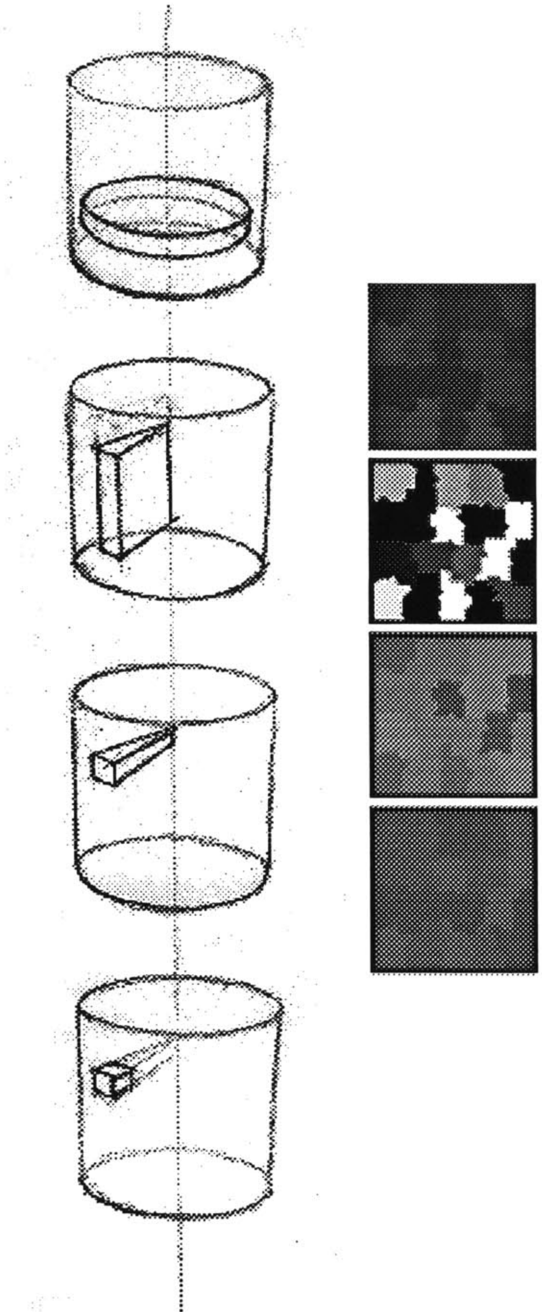

Figure 25. Four examples of color zones and the color choices they allow. The top zone allows darker colors of any hue and chroma. The zone bellow allows any value and chroma but a limited amount of hues . The third zone allows light colors of a single hue and any chromas. Fimally the bottom one allows colors with high chroma, high value and a single hue.

3. Color zones in the Munsell color space

Definition

As stated above, color zones are also sub-volumes of the Munsell color space. Their principal function is to signal to the color containers in which region of the color space the appropriate colors for their current role can be found.

The Munsell spatial configuration of color allows us to define zones within which all color will have special characteristics. They can be viewed as constraints or limitations on the choice of colors that can be made by a group of objects. A zone can limit the choice on only one dimension or on several. The smallest possible zone is a single color. The examples of **figure 25** show different zones configurations with the visual effect of the color choices that they allow.

Color zones take their full meaning when they are used to partition the color space. The different zones configurations presented in **figure 25** can be meaningfully combined together to produce a set of guiding constraints for the color management method. Such a system of color zones indicates to the management method which part of the color space can be used by the objects of the image, i.e., by the color containers. The relationship that exists between the zones determine the type of visual effect that will be acheivable in the dynamic image.The different extents of the zones and the distances that separate them decides of the color contrasts that will appear in the image.

Perceptual levels

The principal function of a system of color zone is to establish in the dynamic mapping image a set of perceptual levels. In the dynamic mapping image presented in the opening example, three perceptual levels are used, a background level, a context level and a foreground level. These three levels can be established by defining three color zones.

Two factors determine the extent and location of each zone in the set:

• The the amount of contrast appropriate for the associated level, which is related to the extent of the zone along the three dimensions of the color space.

• The amount of contrast between the associated level and the other levels, which are related to the distances between the zones in the color space.

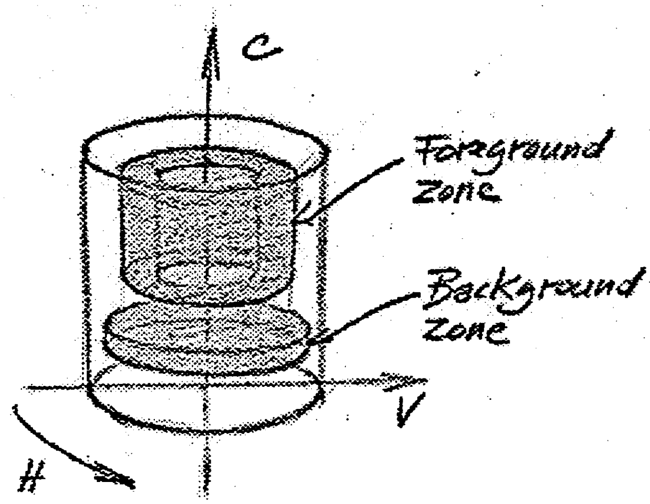

Figure 26. A simple color zone system: low values in the background, higher values and high chromas in the foreground

The appropriate amount of contrast at each level is related to the role that will be played by the graphic objects at this level. For instance, at the foreground level, the graphic objects are involved in the current focus of interest in the image. This is a level where the most "semantic activity" takes place, therefore, the objects will need more leeway in their color choices and in their variations. Consequently, the color zone associated to the foreground level should have a wider extent, i.e., allow a larger amount of contrast in at least one of the color dimensions. The foreground level could need a vast amount of contrast in hue and value and a small amount of contrast in chroma. Such a zone would allow the objects at the foreground level to have colors with a wide selection of hue and value but all objects would have color with similar chroma. The background perceptual level, in turn, may need a large amount of contrast in hue and chroma and a small amount of contrast in value. The resulting color zone would have to constrain the color of the graphic objects at the background level to have small differences in value (low contrast) but would allow the objects to take a wide variety of hues and chromas. **Figure 26** shows the zone configurations corresponding to these specifications.

To be differientiated by the user, the perceptual levels must be separated by enough contrast. In the color space, this requirement translates into a sufficient distance between the color zones attached to the levels. The definition of the distances between the zones, in turn, determine the locations of the zones in the color space.

The amount of contrast between the zones is determined by the roles that the visual levels play in the image. In the three levels taken as examples, the salience of the foreground level should be strong relatively to the salience of the two lower levels. The objects at the foreground level should always be very proeminent relatively to all the other objects in the image. The difference in salience between the context and the background level should be smaller. The objects in the context can have an appearance relatively close to the background, since background level and context level form together the informational, visual context of the image. It will be seen further that the design of a set of color zones that is successful at creating visual levels that are percieved as such by the user is not as simple. The optimal inter-zones distances and zone extents has to be determined with the help of visual knowledge that is not yet available.

Adaptive image

If the color containers have the ability to reflect and control the semantic structure of the image in its parts, the color zones have the ability to control it globally. Systems of color zones can be modified to establish new visual levels. The new levels can be appropriate to a new semantic situation and the new demands it makes on the visual interaction. The dynamic mapping image can be viewed as adapting to the current information presentation situation.

In the introduction to this thesis, the dynamic mapping image was defined as a visual interface to a rich geographic data base. A large visual data base can be adressed in many different ways that will produce many different image configurations. During the course of an interactive session, the user may need to change his angle of view toward the data base he his working with. To adapt to this new angle, the relative importance of the visual levels may have to be modified. A simple example would be an increase in relevance of the details contained in the topographical background. At some point in the interaction, the topographic background will only help conveying the location in space of the objects in the

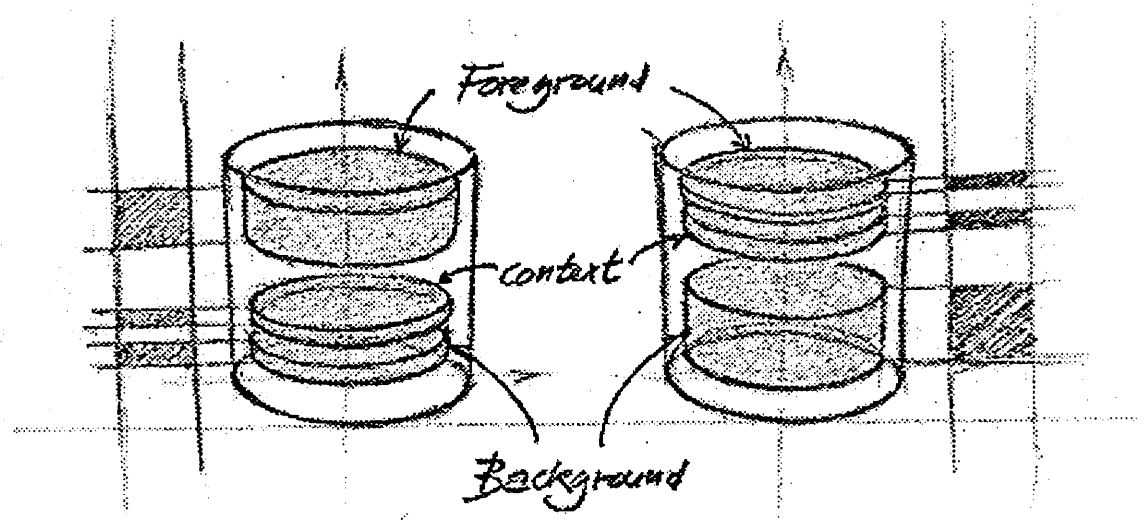

Figure 27. A simple example color zone system adaptation

upper levels. In this case, a simplified background is sufficient. At a later point in the interaction, more complex topographical details might become relevant to the problem at hand, causing a need for a modification of the background visual level. The background level will need to use a larger part of the color space to display the new detail efficiently. Such a modification necessitate a reassessment of the whole set of color zones. The background color zone will be extended, and the context and foreground zones will have to be reduced to keep the optimal visual distances between levels **(figure 27)**. With such adaptive operations, the quality of the interaction with the dynamic image can be maintained despite evolutions in the image configuration.

4. Knowledge relevant to the color management method

Predictable, visual operations

As described in this chapter, the color management method will allow an automated module to operate on the dynamic mapping image in a controlled manner. The relative saliences of graphic objects groups can be modified, the global visual structure of the image (visual levels) can be adapted. These modifications can be referred to as *visual operations*. Indeed, any modification applied to the set of color containers or to the set of color zones results in a visual effect in the dynamic image.

The color management method will be useful only if its visual operations have predictable effects. The effect of a visual operation is predictable when the intention of the operation is acurately perceived by the user. A typical visual operation in dynamic mapping images is a displacement of a group of graphic objects from the context to the foreground. The operation can be described as follow. The group of objects, because of its appearance, is perceived as a part of the context. Its degree of salience is similar to the other groups in the context level. As a result of a context-to-background displacement, its degree of salience increases to a point where it is *perceived* as part of the foreground.

The success of this kind of operation is possible only if the management method possesses the knowledge necessary to establish the appropriate visual distances between context level and foreground level. The visual distances that the system of color zones is meant to enforce are elusive, relative values. They are dependent on the characteristics of the human visual system , and the content of the image itself. The distances are influenced by the amount of visual contrast necessary to the human visual system to discriminate between visual levels. They are also influenced by the number of graphic objects in the image and the image complexity. The knowledge that is needed to establish the correct visual distance is, therefore, both perceptual and graphic.

This knowledge is not yet available in an integrated manner. It has been said in the previous chapter that the available, reliable data is valid only for simplified experimental situations. In the absence of the necessary visual and graphic knowledge, the method of color management cannot yet be implemented in an automated control module. But it will be seen further that it can be implemented in an interactive experimental system that will be used to help the acquisition of the necessary knowledge.

Knowledge aquisition

Dynamic mapping in the computer environment is a new, emerging technology. Graphic designers or cartographers haven't yet had time to build up any expertise with these new visual environments. The visual and graphic knowledge necessary to the method of color management cannot be acquired by classical knowledge engineering technics like the interview of field experts. Nevertheless, graphic designers and cartographers do have expertise in more current visual environments that can be used toward the development of knowledge in dynamic mapping.

An experimental dynamic mapping environment can be build. Interactive control over the visual configuration of the dynamic image can be made available to an expert in graphic and visual matters. With such an experimental system, the graphic designer will be able to use his expertise of current media to shape the dynamic image. As it was stated in section 3.2.1., it is one of the main competence (or rather expertise) of graphic designers to be able to carry design principles across different media. The graphic design principles that are independent of a visual medium can be used by an expert graphic designer to begin shaping the dynamic image. Also, in practicing with the dynamic image, the expert graphic designer can uncover the graphic design principles that are specific to the dynamic image.

Giving to the graphic designers the means to explore the new dynamic mapping environments seems to be a promissing process for the acquisition and development of the knowedge that is necessary to their control. By giving the controls to an expert able to adapt his expertise to the new visual situation at hand, new knowledge can be generated that will be specific to dynamic mapping and that will have inherited some of the proven expertise developed for current media.

Two kinds of knowledge seem to be relevant to the management of color in dynamic mapping. The first concerns the different ways of establishing visual levels in the image. The second kind concerns the distances between zones and the extent of the zones.Visual levels can establish with different combinations of the three components of color, hue, chroma and value. Some combinations may be more appropriate than others in different situations. A task of the expert graphic designer will be to find these combinations and to experiment with them in order to make an evaluation. Each combination will yield guidelines to configure the system of color zones. These guidelines will be complete when the proper distances between zones and their extent will be known. A subsequent task will be to perform systematic visual experiments with every kind of configuration, to find these values.

The experimentation system that will be used to perform such an exploration will provide to the expert designer with a simulation of a dynamic mapping image. This image will contain the graphic objects that are usually present in maps. It will also provide the means of generating the color space projection of the image, and to organize it using color zones and color containers. Interactive control over the zones and the movement of containers will be available. Using such a system, the expert designer will be able to set up different image configurations using zone control. Their performance in supporting dynamic visual operations will be testedby using the control of color containers. The experimental system that will be presented in the next chapter follows this outline.

Chapter 5. The graphic, experimental system

1 Overview

Purpose

In the previous chapter, a method of management for the use of color in dynamic mapping is proposed. It is a framework for the control of the evolving color situation in a dynamic image. Two complementary sets of tools are used to take advantage of the mapping relationship that exist between the image and its underlying color space:

• The color containers are used to apply modifications to the colors of the graphic objects in a manner consistent with the semantic structure of the image.

• A system of color zones are used to guide the evolution of the containers in the color space.

With this framework, all the controls are in place, but the method is still blind to the perceived effects of the color modifications it will make. This method will become a control mechanism for an automated color management module only if visual and graphic knowledge is made available to it.

The principal purpose of the graphic experimentation system described here is to help acquire the knowledge necessary to inform the method of color management. The knowledge will be acquired by giving the control of the image's color situation to a graphic designer. The interactive control of the color situation will take place through the existing framework that was originally designed to be used by an automated control module. By playing the role of the automated module, the designer can use his expertise with controlling complex color situations. The information that is produced by the designer's control, e.g., the data relative to the use of the color resources, can be recorded. This method has the advantage to be much more focused on the visual problems at hand than an interview conducted by a knowledge engineer. The designer's visual problem solving abilities can be observed directly, avoiding the mediation of verbalization, which seems to be a problem with complex visual matter.

A dynamic mapping prototype image

The principal element of the experimentation system is a prototype of a dynamic mapping image. It provides the expert graphic designer with a graphic environment where the visual situations expected from typical electronic mapping can be simulated. The image consist of a set of graphic objects organized into a simple hierarchy of groups. The color of objects can be controlled at every level of the hierarchy.

The categories of objects that are available to the image are usually found in printed or electronic maps. Four categories of objects are supported by the prototype image **(figure 28)**:

• Areas • Lines • Icons • Text labels

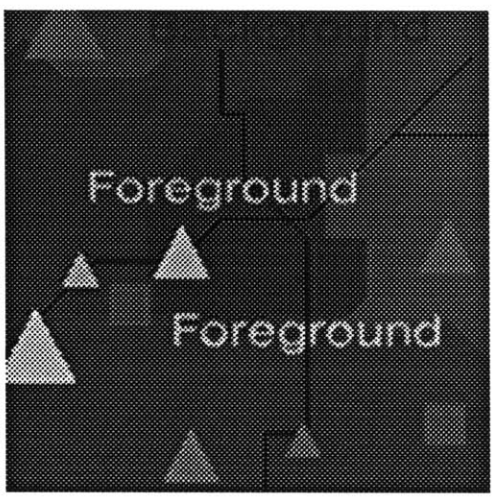

Figure 28. The four graphic categories

Areas simulate the colored surfaces that are used in mapping to differentiate the regions of the topography. They are simple polygons that can have arbitrary shapes and sizes. Lines simulate all the linear topographic information that can be represented in maps, e.g., roads, water ways, borders. They can follow arbitrary paths. Areas and lines are linked to the topographic background of the map, and as such, have a static position in the image. Icons simulate the information that is usually represented in maps as pictograms. They are the main dynamic elements of the map. They denote the information that is not purely topographic and is related to the theme of the map. In the opening example, the theme is forest fire monitoring and icons are used to represent fire sites, fire fighting units, medical facilities and so on. Like areas, they are simple polygons. Their size is fixed, and their shape can be arbitrary. The text labels could be related to either topographic or thematic information. In the simulation, their behavior is similar to the icon's behavior. Icons and text label, are related to dynamic information, and as such, have modifiable locations.

The objects in each category are simple geometric shapes. One single color is attached to each category. Graphic situations similar to the situations found in realistic mapping can be constructed by combining objects of the four categories. The complexity of the situations can be varied in two ways:

- The shape of the objects themselves can be of arbitrary complexity.
- The number of the objects in the image can be varied as well.

This prototype of a dynamic image allows the creation of examples within a range of complexity that starts at simple tests patterns and can go up to very complex map simulations. As a consequence, it is possible to create images with color situations that are complex enough to pose realistic graphic problems. This enables the results obtained with this knowledge acquisition method to be usable outside the experimental conditions.

Graphic objects in dynamic mapping can be organized in many ways. This organization should be tightly related to the semantic organization of the image. Ideally, the organization of objects in a dynamic mapping image should be flexible and reconfigurable. For the sake of graphic experimentation, the objects in the prototype image have been organized by graphic categories. A simple hierarchy of graphic groups has been established. At the top level are the four categories of graphic objects described above, areas, lines, icons and text labels. Within each category can be found groups of objects. Each one of these groups contain an arbitrary number of single objects **(figure 29)**.

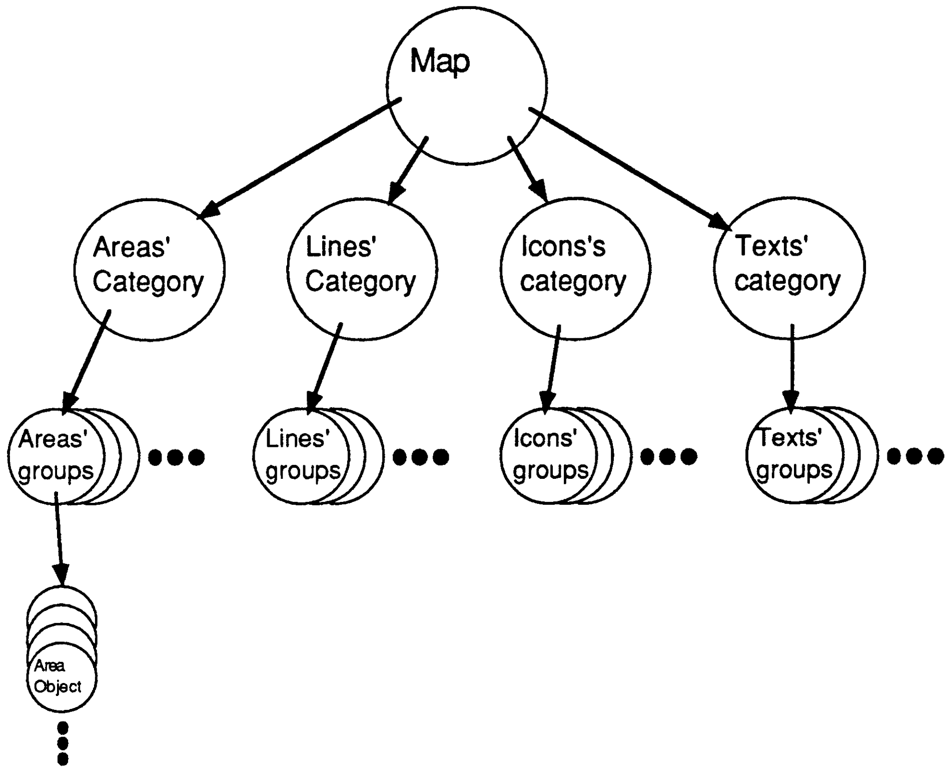

Figure 29. The organization of objects in the prototype mapping image

Grouping the objects of the prototype image by graphic quality has relevance to realistic mapping. Objects that denotes similar entities are usually represented by similar shapes. Roads on a map are represented by lines, and it makes sense to classify the roads in the same group. Rivers are also represented by lines and can be assigned their own group. In turn, it is acceptable to classify roads and rivers in the same super-group since both entities can be viewed as transportation tracks. It could be argued that, in some situations, roads (represented by lines) could be classified in the same group with road intersections (represented by icons). But, even if this is an oversimplification, a general coincidence exists between the classes of shapes and the classes of entities that are represented in maps. This coincidence justifies the classification of objects in the prototype image by graphic quality. With such a classification, the graphic and color relationship in the image can be considered without the clutter of specific semantic example. The semantic structure of the image is stripped to the bare bone. All that matters semantically is that the groups of objects in the prototype image denote different classes of entities, even if these entities are not known. The semantic structure of the image is reflected in the graphic experimentation by the hierarchy of graphic objects in the image

The control of color in the dynamic image

The control of color in the prototype image is a direct implementation of the color management method presented in chapter four. The experimentation system establishes a dynamic relationship between the image and the Munsell color space. The RGB specification of colors is present in the system only for display purposes. All the color manipulations take place within the perceptually consistent Munsell color space.

Color containers are supported by the experimentation system. As the management method requires it, color containers are used to bring the semantic structure of the image into the color space. All the groups of objects in a category will be included in a color container. All the objects in a group will be assigned a container as well. A two level set of interrelated color containers becomes the projection, in the color space, of the image semantic structure. The two levels will be called super-containers and object-containers. Four super-containers control the four categories of objects. Nested in every super-container, an arbitrary number of objects-containers can exist, each holding groups of single objects. The color of every graphic objects is defined relatively to its corresponding object-container, using the normalized Munsell vectors presented in chapter four. In the same manner, the object-containers' boundaries are defined relative to their corresponding super-containers. This combination of color container nesting and of relative definition of color values offers a dynamic control structure of the relevant color relationships in the image.

With this control structure, the color relationships between elements of the image can be modified in two distinct ways:

• Direct modifications

• Indirect modifications

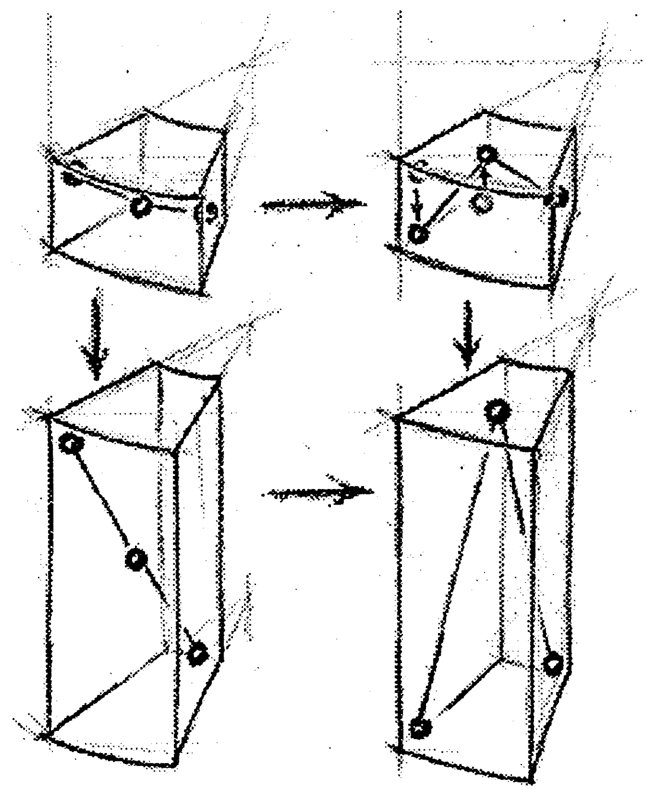

Figure 30. The direct and indirect modifications of the color constellations. Direct modifications follow the horizontal arrows. They cause a change in the constellation's geometry. The indirect modifications follow the vertical arrows. The cause a change in the constellation's amplitude.

With a direct modification, a relationship between two or more containers, or two or more colors can be modified by changing directly their color specifications. A container can be made wider than its siblings, or a color can be made redder or brighter that its sibling. Such a modification changes the aspect of the relationship. In the case of color, it can be said that the color constellation is changed in its shape (a topological change). The indirect modifications are the changes that affect the content of a container when its boundaries are moved. With definition of color values relative to the containers, every change in the containers shape affects the relationship that exists between the elements of the containers content. As stated in chapter four, this kind of modification affects the color relationship in its amplitude only. The diagram in **figure 30** gives a visual explanation of the two kind of changes.

The relative definition of all color values in the image implements a simple inheritance scheme through the containers structure. The modifications applied to the boundaries of a super-container will be automatically reflected down to its object-containers and the single colors they hold through a series of automatic, indirect modifications. At the level below, the modifications applied to object-containers will also be reflected to the color they hold by the same process. Through direct and indirect modifications, color relationships can be controlled at every level in the color containers hierarchy. Precisely, at the level of graphic categories, at the level of groups of objects and at the lower level of objects' colors within a group.

This multi-leveled control of color is relevant to dynamic mapping. In dynamic mapping, color relationships have to be controlled globally as well as at the level of object groups. An example of relevant, global relationships is the relative saliency between the graphic objects in the background of the map and the graphic objects in the upper levels (context and foreground). Another example is the relative salience between different groups of icons. The groups that are part of the foreground must all appear more salient than all the groups that are in the context. Such global relationships can be controlled by operating on super-containers. A relevant relationship within a group is the visual differentiation between the objects of that group. For example, a group of contiguous areas can be part of the background. These areas can be differentiated by controlling the color relationship that exist between them. Their hue component can be kept apart by spreading them in the hue range of their container through a direct operation. Then, their hue difference can be adjusted by operating on the hue boundaries of their container. The control structure that is provided by the color containers' hierarchy allow both kinds of relationship to be controlled simultaneously.

The hierarchy of color containers also allows the global and local relationships to be correlated. At the global level, the salience of a group of objects may need to be reduced. This reduction of salience should be accompanied by a reduction of the amplitude of the relationship that exist between the object of the group. Indeed, if a group of objects becomes less relevant to the display, its internal relationship becomes less relevant as well. The color container hierarchy can support such an operation: the reduction in salience can be performed by a lowering of the group's container in the value dimension. It can be accompanied by a reduction of the extent of the container, which will result in a reduction of the amplitude of the groups internal relationship.

This control structure has been established with the purpose of simulating the controls and interactions to be expected in dynamic mapping. It is meant to be driven by an automated color management module. In this research, as it was stated in chapter four, it will be used interactively, to develop the graphic and visual knowledge necessary to the method of color management . The color zones are also supported by the experimentation system. By operating directly on the containers control structure, a graphic designer is able to manipulate a multi-object, multi-layered image. Visual levels can be established interactively and color zones can be set to enforce these visual levels.

Visual knowledge acquisition

The process of knowledge acquisition that the experimentation system will support has been briefly presented in chapter four. The control of the color situation in the dynamic image are given to a graphic designer. Using his expertise with the use of color in complex graphic compositions, the designer performs a series of visual experimentation which general purpose is to discover a configuration of visual levels that will help the image support controlled dynamic, visual operations.

The purposes, characteristics and dependencies of the visual levels configuration are:

• Visual ordering

• Graphic quality maintenance

It has been explained that visual ordering helps the user parse the evolving image easily. It is a necessary condition to a dialog with the dynamic image. Also the graphic quality has to be maintained throughout the course of the interaction. Graphic quality is dependent on the maintenance of object discernibility and appearance constancy. It is one of the principal hypothesis of this work that both purposes can be served efficiently by establishing a configuration of visual levels in the image. Visual levels will fulfill their purpose under precise visual conditions. Determining these conditions is the main goal of the knowledge acquisition process described here.

The notion of visual level is related to relative salience of the image elements. It is also related to the notion of visual categorization. A visual level exists in an image when the graphic objects at that level are perceived by the viewer as having the same salience and, most importantly, as belonging to the same visual category (the foreground category, for instance). In dynamic mapping, a visual level can be thought of as a virtual container, a region located in the depth dimension of the visual field. Groups of graphic objects can move into it, or be removed from it, according to their current role in the image. The graphic challenge is that all groups of objects also form their own visual categories. When thrown in the same visual level, they have to belong to a same common visual super-category, while not loosing their group differentiation. Visual levels can be thought of as visual super-categories that exist at a higher level than the visual categories in which fall the graphic objects groups. The duality between visual levels and graphic objects groups is reflected in the notions of color zones and color containers that are at the basis of the color management method. This double visual categorization, that has to be made possible by the image visual levels configuration, is the main concern that drives the visual exploration of the expert graphic designer.

Another concern is of the visual experimentation is the need for visual comparisons within one level as well as visual comparison across levels. For instance, at the foreground level, the viewer needs to make visual assessment between the objects of different groups like recognizing to which group some given objects belongs. This is a visual comparison that takes place only within the foreground level. Conversely, the viewer may need to find out the location on the topography of an objects. That operation is a visual comparison between an upper level and the background level, where the topography is represented. Both these operations are linked to the amount of visual distance, or contrast that is appropriate within levels and between levels. The need for both kind of visual assessments further define the characteristics that the designer is looking for in experimenting with visual level creation.

Two distinct sets of visual decisions have to be determined by the designer to create a set of visual levels in the image:

• Choose which combination of restrictions on hue, value and chroma will be used to establish visual levels.

• Determine the distances in the color space that will separate the zones, and the extents of the zones.

A set of color zones can be viewed as establishing a combination of restrictions on the usage of color's three components, hue, value and chroma. For a background zone the usage of value can be restricted to a narrow range, while hue and chroma can be used with no restrictions. The associated foreground level could have small restrictions on value and chroma and none on hue. The combinations of restrictions on the color components usage that is applied to each zones of a set determine the general appearance of the image and, ultimately, the efficiency of the visual levels that are established. A main task of the experimentation conducted by the designer is to explore these combinations and to discover which combinations will be useful. Also, the experimentation should help determine the relative advantages of these combinations in view of the different semantic situations that have to be supported by the dynamic image.

Once a combination of color restrictions is selected, the designer can "fine tune" the set of color zones by adjusting the distance that separate the zones. Their extents along the three dimensions of the color space, also have to be adjusted. The distances between zones affect the amount of contrast that will be perceived between the corresponding visual levels. The extent of the zone affects the amount of contrast that can be possible between the objects displayed at the same level. These two kind of quantities are interrelated. If their proportional sizes are not appropriate, a risk of visual confusion between levels is likely to occur. They are also dependent on the color dimensions. Equal distances have different visual effects along hue, chroma or value axis. These dependencies have to be taken into account as the visual experimentation takes place.

The experimentation procedure was introduced at the beginning of this chapter. It is described further here. An example of a dynamic image is built, from the domain of mapping. Graphic objects of a given degree of complexity are produced with the help of a simple graphic editor supplied with the system. Sets of object groups of the four graphic categories are formed. When a new image is loaded into the system, the set of color containers that will be used for its control is automatically generated. At this point, the image is ready for manipulation. By operating on the color containers, the designer can separate the graphic objects groups into three distinct levels. This is done by interactively restricting the color range defined by each container. By observing the image, the designer can bring each group of objects to a degree of salience that fits a desired visual level. The designer can progressively build the three visual levels concurrently, adjusting their visual relationships until the desired visual effect is obtained. When this process is completed, the bounding box that includes all the color containers in one visual level represents the color zone of that level. The experimentation does not stop there. The visual levels that have been established so far are valid only for a static situation. The next phase of experimentation consist of setting the configuration of color zones. Then the zone configuration can be tested for validity in a dynamic situation. Group of objects are displaced from level to level by moving their associated containers from zone to zone. The designer can enlist the help of other subjects to visually evaluate if the intention of the moves are accurately perceived. If confusion occurs, the visual levels can be refined and tested again.

The knowledge that is obtained by such a process takes the form of series of image configurations, concretized by the data that define the systems of color zones. For every image configuration that is achieved, the semantic conditions or the interaction condition for which it is appropriate can be recorded. The combination of a series of quantified color zones and of knowledge about their appropriateness for different condition, constitute the beginning of the knowledge base that has to underlie the method of color management that is proposed in this thesis.

2. Implementation

System components

The central component of the experimentation system is the *map structure*. It holds and organizes all the information necessary to the control of the map graphic simulation. Linked to this basic structure are visualization components and control components:

• Visualization components:

The map graphic simulation

The map color distribution viewer

• Control components:

Selection tool

Munsell color range selector

Color zones editor

Figure 31 gives a diagram of the integration of these components. The map graphic simulation is the system component where the experiments described in the previous section will take place. It is a window where all the graphic objects organized in the map structure are displayed. The image reflects the current state of the map structure at all time. Every modification to the structure applied by the experimenter is followed by a redraw message to the window. The control of the map graphic simulation is, therefore, an interactive process where the effect of every modification can be viewed immediately by the experimenter.

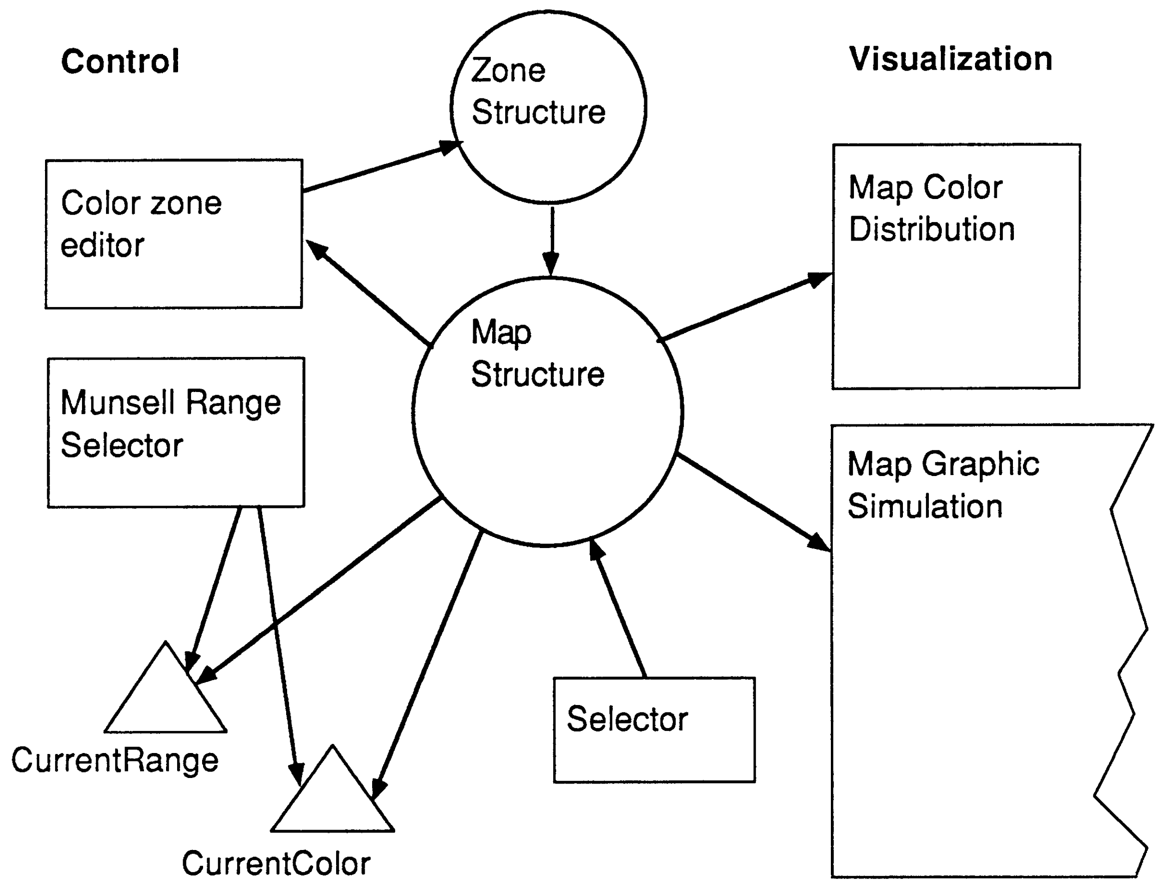

Figure 31. System components

The map color distribution viewer supplies a visualization of all or of selected parts of the color containers structure. It is used by the experimenter as a guide to the editing of the containers structure. Since it is able to represent all the color containers in the map structure, it offers a view of the regions of the color space that are actually used by the map simulation image. This tool will be described further in the following sections.

The selection tool allows the experimenter to choose to which level of the map structure this modification will be applied. The selection process influences all components of the system. When a given level is selected, modifications will be applied at that level, but also, all visualizations will represent the situation at that level.

The Munsell color range selector is the principal interactive tool in the system. Its description is the object of a special section. It is used to select the ranges in the Munsell color space that will define the color containers, and ultimately the color zones. It is used to distort and move the containers across the color space. It can also be used to modify the color specifications of single graphic objects in the system. All direct and indirect modifications of the color situation in the map graphic simulation image are made with this tool.

The color zone editor is used to set the values in the color zone structure. Its is a simplified 2-dimensional version of the map color distribution component. When the experimenter has obtained a visual level configuration that is worth testing in the dynamic mode, the color zones can be set interactively using this tool.

The basic data structures

Three basic data structures are used in the experimentation system:

- The color range structure
- The single color specification structure
- The graphic object structures

These are the building blocks of the map structure. The color range structure is used to store the data that defines regions in the Munsell color space. As such it is used to define color containers as well as color zones. It is widely used in the system. The color range structure includes the specification of the ranges boundaries as absolute Munsell values. It also contains the specification of the boundaries as values relative to its parent range. Relative specifications allow the implementation of the simple inheritance scheme described earlier in this chapter. Following is the definition in C programming language of a color range structure.

```
struct ColorRangeStruct {
    float hue1, hue2;                    /* Range boundaries  as absolute */
    float chroma1, chroma2;              /* Munsell specifications */
    float val1, val2;
    float rel_hue1, rel_hue2;            /* Range boundaries specified */
    float rel_chroma1, rel_chroma2;      /* relatively to the parent range */
    float rel_val1, rel_val2;
    struct ColorRangeStruct *parent_range, *next;
    char *id;
};
```

The single color specification structure is used to store the color data relative to the graphic objects of the system. Similarly to the color range structure, the absolute

Munsell color specification and specification relative to the containing range is stored in the data structure. These two specifications are actually the absolute and normalized Munsell vectors defined in chapter 4. In addition, the regular RGB specification are stored for display purposes. It is important to notice that this is the only place in the system where RGB specifications are used. All color manipulations and analysis are performed in the Munsell color space. RGB specification are used only at display time. Every time a color is changed in the image, through direct or indirect modification, a process updates the three types of color specification. This is the reason for the presence of a pointer to the parent color range of the color. The information stored in the parent range is necessary for this updating. Following is the C language definition of a color specification structure.

```
struct ColorData {
    float   hue, val, chroma;                   /* Absolute Munsell vector */
    float   rel_hue, rel_val, rel_chroma;       /* Normalized Munsell vector */
    int     r, g, b ;                           /* Display specifications */
    struct ColorRangeStruct        *parent_range;
};
```

The graphic objects structures are similar for the four graphic categories. They all include the following fields:

- A geometric definition
- A name
- A pointer to a group structure
- A pointer the a color specification structure
- A pointer to the next object (same graphic category)

The pointer to a group structure is used to give the object its place in the map structure.

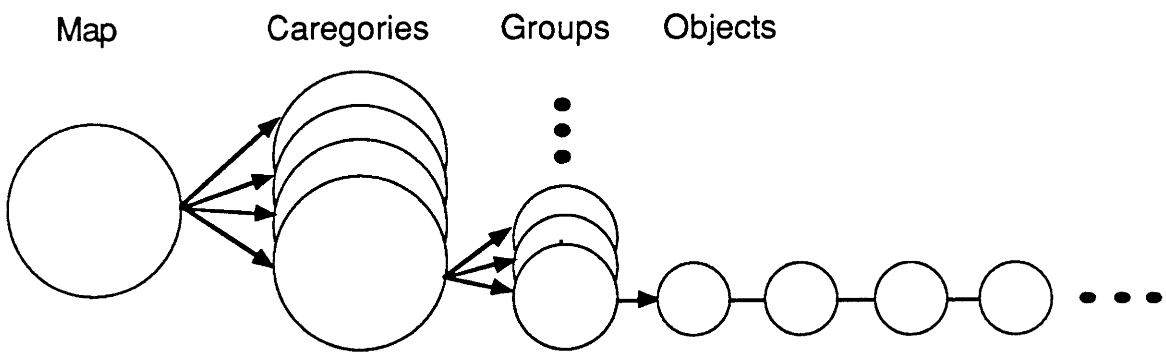

Figure 32. The four levels of the map's structure

The map structure

The map structure is the central component of the experimentation system. As such, all other components are referring to it. It carries the organization of the graphic objects in the image as well as the organization of the color containers .

The graphic objects in the structure are organized in a three leveled hierarchy:

• Graphic categories

• Object sets

• Single objects

At the bottom level, single objects can be accessed separately. They are assembled into lists at the mid level which constitute object sets. At the top level, the object sets are assembled into set lists which constitute graphic categories **(figure 32)**. As it can be seen in the diagram of **figure 33**, the map structure includes four graphic categories, areas, lines, icons and text labels. The map structure is, therefore, a tree with four main branches, each one corresponding to one of the four graphic categories.

The color containers organization follows the same pattern **(figure 33)**. The super-containers are stored at the level of graphic categories. Each category is assigned one super-container which holds the objects containers stored at the level below, i.e., the object sets level. These object containers hold the single colors that are assigned to every object in their corresponding object set. Starting again at the bottom of the structure, the color of every single object is defined relatively to its corresponding object container. Moving up again, the object containers at the object sets level are defined relatively to their corresponding super-containers. This interdependence of the color containers implement the simple inheritance scheme

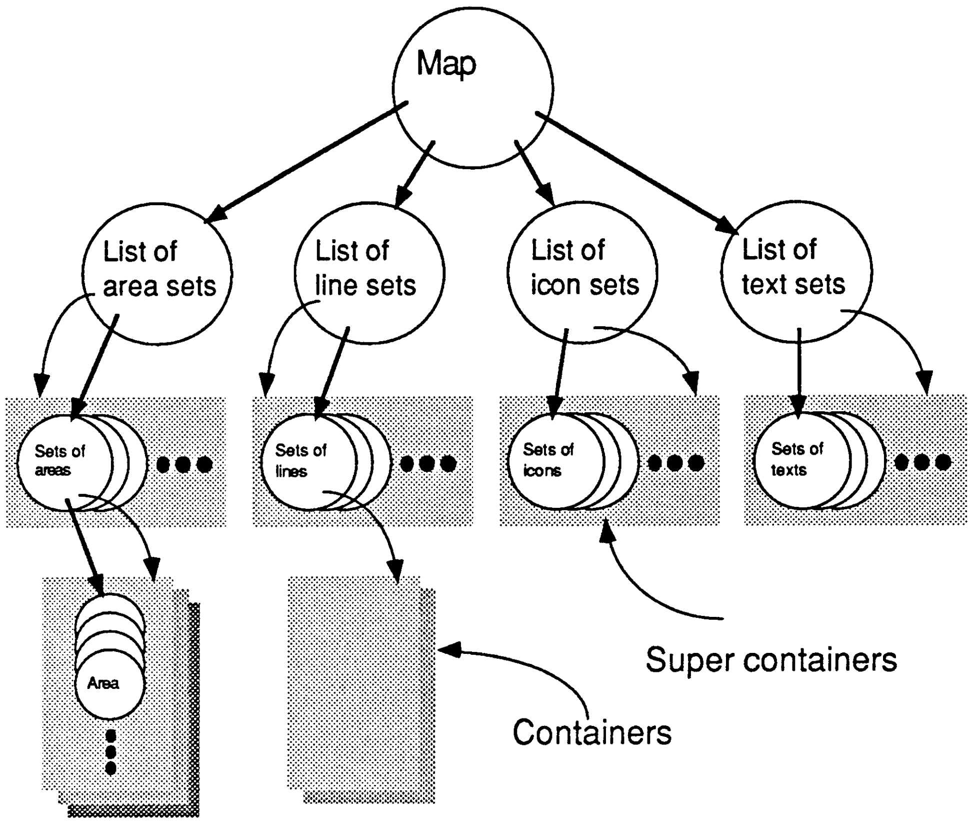

Figure 33. The map graphic simulation's structure

described in the first part of this chapter. The colors of single objects at the bottom of the structure will be affected both by changes made to their corresponding object containers and by modifications applied to their corresponding super-containers.

The three levels correspond to the scope of the modification that can be applied to the structure. When a selection is made at a given level, the color modifications applied will affect all the levels below. In the case of the graphic categories' level, the color of all the objects of the category selected will be affected. At the object group level, the color of all the objects belonging to the selected group will be affected. At the bottom level, the color of single objects can be modified.

Two visualizations of the map structure are supplied by the system: the map graphic simulation and the map color distribution . The map graphic simulation is a window where all the graphic objects present in the map structure are drawn. The drawing function traverses the lower level of the structure in the following order: areas, lines, icons and finally text labels. This order is suggested by the fact that areas and lines tend to be background objects used to represent topographic information. Icons and text labels that usually represent thematic information tend to be at the upper levels of the image, the context and foreground levels. Further, since transparency is not addressed in this work and not available in the system, it is only common sense to draw the objects that have the most extent in the 2-dimensional space first. As stated above, the map graphic simulation is updated after every modification applied to the map structure. The polygon drawing routines that are used are hardware based, which makes the updating fast enough to be un-obtrusive. The font display routines are slower because they are software based and provide antialiasing. Nevertheless, it does not cause a problem since the number of text objects is low compared to the number of polygon based objects in the image.

The map color distribution window provides a view of the current state of the color containers structure. It is a 3-dimensional viewport that looks at a representation of the Munsell color space. The representation is built in such a way that the coordinates of the 3-dimensional world coincide with the coordinates of the Munsell space. To avoid un-necessary virtual camera movements that would bring only confusion, the settings only allow the camera to circle about the Munsell volume around the x and the y axis. From the point of view of the experimenter, these movements appear as controlled rotations of the color solid. By using a set of two sliders, the experimenter can pivot the space to examine the current state of the color model **(figure 34)**.

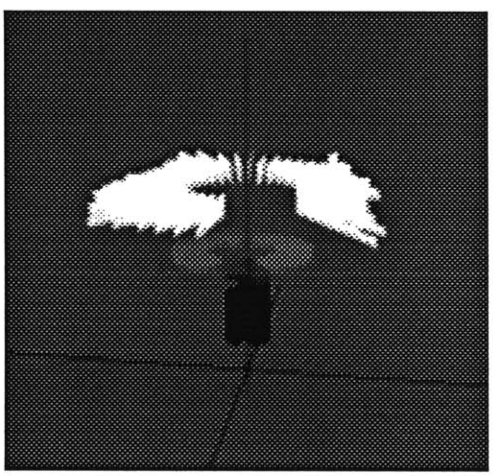

Figure 34. The 3-d view of a partially used Munsell color space offered by the Map Color Distribution tool.

The phrase *map color distribution* denotes the parts of the Munsell color space that are used by the map at a given instant. When all the color containers that are present in the map structure are displayed in the viewport, the image that is obtained is a 3-dimensional representation of color space regions used by the image, i.e., the map color spatial distribution. By examining this representation directly, the main color relationships of the image can be visually assessed. The distances between color containers can be compared as well as their relative extents. The experimenter is given the option to display all or parts of the color containers structure. Also when a container is modified, by using the Munsell range selector, the movement apply to the container is reflected in real time on its representation in the viewport. With these two features, the viewport can be used as a visual guide for the editing of color containers. While editing a color container the experimenter can constantly refer to its relationships with all the other containers.

The map graphic simulation and the map color distribution viewport constitute the principal visual tools of the experimentation system. Together, they provide a visual implementation of the image/color space relationship that is at the base of the color management method that is proposed in this thesis.

The Munsell color range selector

The Munsell color range selector is used to control the color situation in the map image. It goes a few steps further than the palettes available in commercial graphic applications. Its main particularity is its ability to select regions of the color space (ranges), in addition to selecting single colors. The tool is an extension of the Munsell color selector developed in the Electronic Publishing group of the Media-Laboratory by Walter Bender **(figure 35)**.

It is based on a orthographic projection of the Munsell color space. Two windows are used to select a color range. The left window (the hue window) presents a planar view of the Munsell space, actually an horizontal section through the space. A hue sector can be selected by using two radial handles. The boundaries of the sector constitute the hue boundaries of the selected range. The right window (the chroma/value window) presents an elevation of the Munsell space. On each vertical half-windows are represented vertical sections of the space, commonly called Munsell leaves. The two Munsell leaves correspond to the hue boundaries of the currently selected range. A set of value boundaries and a set of chroma

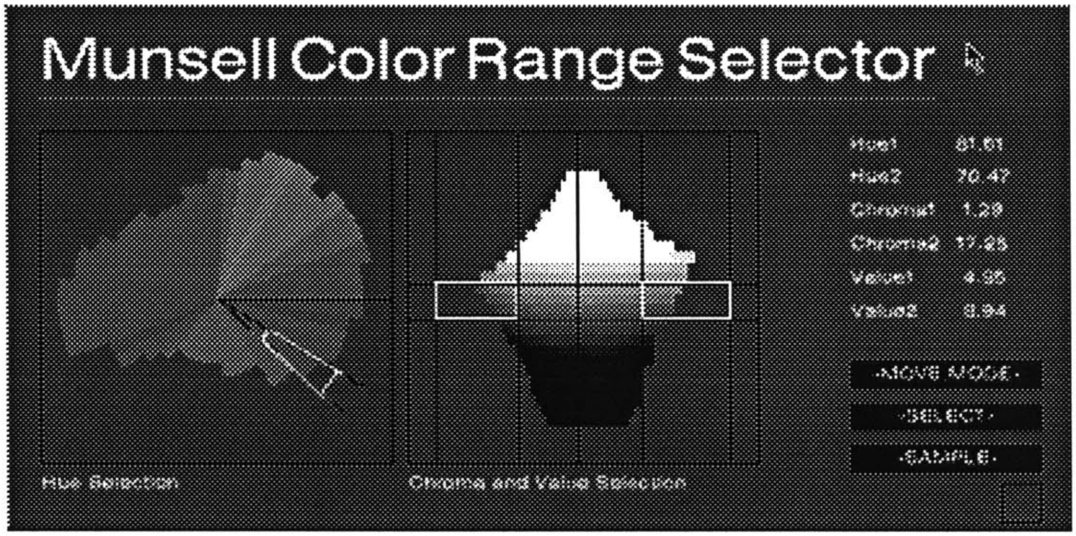

Figure 35. The interactive tool used to define sub-volumes of the Munsell color space

The 4 handles determine a rectangle that represent the value and chroma boundaries of the selected range.

The two selection windows are inter-dependent. For instance, the horizontal section of the Munsell space that is represented in the hue window correspond to the midpoint in value of the currently selected range. If the value range is modified in the chroma/value window, the section in the hue window is updated accordingly. Similarly, the Munsell leaves that are presented in the chroma/value window are updated if the hue range is modified in the hue window. These features provide a view of the color that are included in the range and facilitate the process of selection.

When a single color needs to be selected, the range selector can be changed to single color mode. The color is selected similarly to a color range, but only single handles are available in the windows instead of pairs.

The Munsell range selector is connected to the map structure through the intermediary of two global variables **(figure 31, section 5.2.1.)**:

• CurrentRange

• CurrentColor

When the range selector is used, it always modifies one of those two globals according to the current mode. In the case of the range selection mode, the range of the color container corresponding to the selected group or category on the map structure is assigned to the global CurrentRange. As a first consequence, the range selector displays the color container's range as it currently stands. The experimenter can then modify it. The modification is applied directly to the selected container. Because of the underlying updating system, the change in the container structure is immediately echoed in the map color distribution viewport, and the visual effect of the modification on the map graphic simulation is immediately visible. The process is exactly the same for the selection of a single color. The change from range to color mode is made automatically by the system when a selection is made. Simply, the mode is color only at the bottom of the structure where only single objects can be found.

As it is designed, the Munsell color range selector provides the experimenter with an interactive, real time control of the image color situation.

The implementation of color zones

The system of color zones is implemented with a simple data structure that stores the specification of each zone as color ranges. Following is the definition in the C programming language of the color zones structure:

```
struct ColorZoneStruct {
    struct ColorRangeStruct      *foreground_zone;
    struct ColorRangeStruct      *context_zone;
    struct ColorRangeStruct      *background_zone;
};
```

In this experimentation system, only three zones are considered, foreground, context and background. The question of determining the number of visual levels that are distinguishable by a viewer and that would be useful to a dynamic map is an important question, but does not fall within the scope of this study. It has to be established first that these three basic levels can be established in the image using the three dimension of color. When this hypothesis is verified, and the visual means to do it will be described, it will be possible to assess how many visual levels can be usefully added to the dynamic mapping image.

As stated earlier in this chapter, the color zones can be set when the experimenter reaches a visual level configuration that is worth testing in the dynamic mode. When a visual level configuration is established, the color container structure assumes a shape that implicitly defines the zones. The bounding box common to all the object-containers at one level defines the color zone for that level.

To set the zones, the experimenter only has to concretize this bounding box using the color zone editor. The color zone editor is a simplified version of the color range selector. It also has a hue and a chroma/value window. Both windows display 2-dimensional views of the color containers structure. These representations help the experimenter find the bounding boxes that enclose all the containers at all visual levels. The experimenter can, then, set the three zones interactively with the handles available in each windows by making the handles coincide with the limits of the bounding boxes.

Testing the visual level configuration in the dynamic mode is done by displacing groups of objects from zone to zone, and evaluating the accuracy of the move's visual effect. The level configuration is valid when the intentions of all the possible moves are perceived correctly by the experimenter and by other subjects. Facilities are made available by the system to move selected groups of objects from one level to another. The move that are tested are:

- Background to Context
- Context to Background
- Context to Foreground
- Foreground to Context

When the visual level configuration needs to be improved, modification can be applied directly to the color zone structure by using the color zone editor or for more radical modifications, the experimenter can go back to the color containers structure and modify it using the color range selector.

Chapter 6. **The visual experiments**

1. The visual experiments setup

The two principal goals of the experiments presented have to be briefly reviewed. The first goal is to explore different combinations of hue, value and chroma restrictions used to establish distinct visual levels within a dynamic image. Their efficiency at creating easily perceptible visual levels is evaluated as well as the advantages and drawbacks they present from the standpoint of dynamic mapping. The second goal is to determine the visual distances between levels and the extent of each level. These quantities correspond to distances and extents in the Munsell color space and ultimately determine the set of color zones that will enforce the visual levels.

The visual characteristics of the three levels are also reviewed here:

• The *foreground level* contains the graphic objects that are the main focus of the interaction at a given instant. The user focuses most of his attention on this level. It should be the most salient visual category. This part of the image should be perceived first, without visual competition from the other levels.

• The *context level* contains the graphic objects that are secondary to the main focus, but need to be present because they supply an informational context. The objects at this level should not be perceived as part of the background, but they should recede enough to form a category distinct from the foreground level. Most of the image's evolution consists of objects' groups moving between context and foreground. The experiments show this is a difficult visual level to establish.

• The *background level* contains the representation of the topography. In the two upper levels the graphic objects form a discontinuous image (they do not cover the whole 2-d space). However, the background level forms a continuous image. The areas it contains have common boundaries and fill the 2-d space. Lines, icons and text labels are part of the background and are represented over this continuous backdrop. The background level contains its own sub-levels that have to be perceivable. As a visual category, the background should visually recede from both upper levels. However, its graphic content is complex, so the color zone assigned to it should provide enough flexibility to make each of its constituent objects perceivable.

The experimental procedure follows three phases:

• The first phase consists of preparing the prototype dynamic image that serves as a testbed for the visual experiments. The shapes and numbers of the graphic objects it contains are chosen to create visual conditions appropriate to the goal of the experiments.

• In the second phase, visual levels are interactively created by shaping the color containers' structure. The operator seeks to create visual categories in the image that fulfill the requirements reviewed above.

• The third and final phase consists of setting the zone system according to the levels established in second phase, and to test the validity of the levels in the dynamic mode. This is done by making groups of objects travel between levels. At this point the operator, with the help of other subjects, can check that the visual levels remain distinguishable despite their changes in content. Also, the perceptual accuracy of level-to-level moves must be checked, (e.g. a background-to-context move is accurately perceived as such by a subject).

The prototype dynamic image is configured to serve the goals of the experiments, regardless of a particular mapping situation. The goal of the experiments is to create visual levels enforced by color zones. Therefore, the main function of the image is to help visualize these levels. Three simple choices are made to insure this functionality:

• The total number of objects in the image is large enough to insure the presence of many objects at each level. Three distinct levels will only become apparent if enough objects are present in each.

• Similarly, the number of objects in each container has to be large enough so the color constellation they form visually describes the color range defined by their container.

• Further, the color constellation formed by the objects covers the entire color range in order to give a complete visual account of the container's range. **Figure 36** illustrates the color constellation assigned to each object group in the image. This constellation insures that the limits of the range and its middle region are represented in the objects' colors.

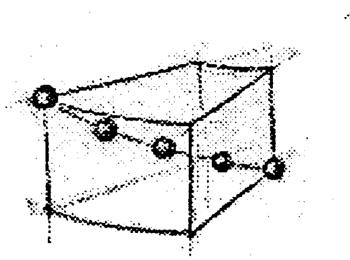

Figure 36. The color constellation that is used in the experiments

The image is simple with respect to the shapes of its objects, yet contained enough groups of objects to allow the building of the three visual levels. In the second phase of the experiments the image contained the following:

- Background
  - 1 group of areas, 20 objects
  - 2 groups of lines, 3 objects per group
  - 2 groups of icons, squares and triangles, 5 objects per group
  - 1 group of text labels, 30 pixels high, 5 objects per group
- Context
  - 2 groups of icons, squares, 5 objects per group
  - 1 group of text labels, 30 pixels high, 5 objects per group
- Foreground
  - 2 groups of icons, triangles, 5 objects per group
  - 1 group of text labels, 30 pixels high, 5 objects per group

The background level contains more objects than the upper two levels that belong to the four graphic categories. This is justified because the background image is related to topographic information, which usually needs a large number of these four kinds of graphic objects. The upper levels each contain 15 objects . This number is large enough to obtain a sufficient visual description of the levels. An optimal number of objects at these levels is dependent on the objects sizes relative to the total image sizes. 15 objects at each of the upper levels is sufficient for the visual task at hand.

Simple square and triangular icons are used. These two distinct shapes are helpful in the process of establishing visual levels. When the levels are not yet established, using identical shapes in the same level helps the operator differentiate them.

In the third phase of the experiments, when the levels are tested in the dynamic mode, the groups of objects are moved across levels. The number of objects in a level changes with each move. In addition, objects at the same level can be of different shapes (e.g. triangles and squares can belong to the same level). With these new conditions the occurrence of visual confusion across levels can be detected. As stated above, the accuracy of level-to-level moves can be checked.

In this series of explorations, the image size was as large as the screen permitted. A 1000x1000 pixel area on a 100 dpi screen. The total size of the screen is 1280x1024 pixels. The visual angle subtended by it was the one usually subtended by full screen images in current mapping applications using this kind of display.

Before describing a series of experimental examples, it is important to present the simple heuristic principle used as a general direction for the establishment of visual levels. The principle states that darker colors should be assigned to objects with large spatial extent (areas) and to objects in background level. Conversely, brighter colors should be assigned to objects with small spatial extent (lines, icons text labels) and to objects in upper visual levels. This simple principle is justified by an aspect of the human visual system, namely, the perception of hue and chroma (color's chromatic components) tends to be hampered when objects are displayed on a bright background. In these conditions the human visual system seems to concentrate on the perception of the value contrast between the darker objects and the brighter background. As a consequence, the objects appear more as silhouettes and very little chromaticity is perceived. This unfortunate situation occurs easily in electronic images when graphic objects with a wide spatial extent are assigned bright colors. The electronic image radiates from the screen, unlike printed or painted images that are reflected. A large expanse of bright screen space radiates a lot of light and the perception of the chromaticity of the objects displayed over it is greatly affected. Therefore, limiting the size of the brighter surfaces creates the best perceptual conditions for an electronic image. The chromatic components of color, hue and chroma play an important role and these visual conditions insure that they are perceivable. This simple heuristic allows to eliminate from the experiments all images that use a light background and build progressively darker upper levels. Such images are commonly used in traditional, printed mapping and are conceivable in electronic mapping, but this simple heuristic principle justifies their safe elimination.

2. Examples

Three examples of visual experiments are presented. They have been chosen because they give a good account of the interactions between the three components of color in the creation of visual levels. In the first example an attempt is made at creating three visual levels using only hue restrictions. The reasons why this attempt fails are examined. In the second example, restrictions on chroma are introduced. Evidence for the important role played by the control of chroma in establishing visual ordering in dynamic images is exposed. In the third example, hue restrictions are added to restrictions on value and chroma. This is the most successful restriction combination. Its possibilities and the compromises that come with it will be presented.

Figures 37, 38 and **40** present the image resulting form the experiments. The images appear in their final state, after their visual level configuration has been tested in the static mode and dynamically.

Example 1, value restriction only

In this example, only value restrictions are used. This means that at every level, the graphic objects can take any possible hue and chroma specifications. **Figure 37** shows the appearance that the zone structure assumes. The zones occupy the entire extent of hue and chroma, as restrictions are applied only to the value axis.

Only restricting value seems an attractive solution. At every visual level, the full range of hue and chroma would be available to the designer for expressing information. The experiments demonstrated that using only hue restrictions is impractical. The type of image that such a configuration produces has little potential for dynamic mapping.

Figure 37 presents the image generated by this experiment. The visual levels are difficult to establish. Three distinct visual levels appear only when the zones are given a very narrow extent in value. The distance between them should be as large as possible. When three perceptible levels are finally apparent in the image, the color zones are three narrow disks in the color space with a large unusable space separating them. The color zone structure can be seen in the diagram and the 3d-view of **figure 37**.

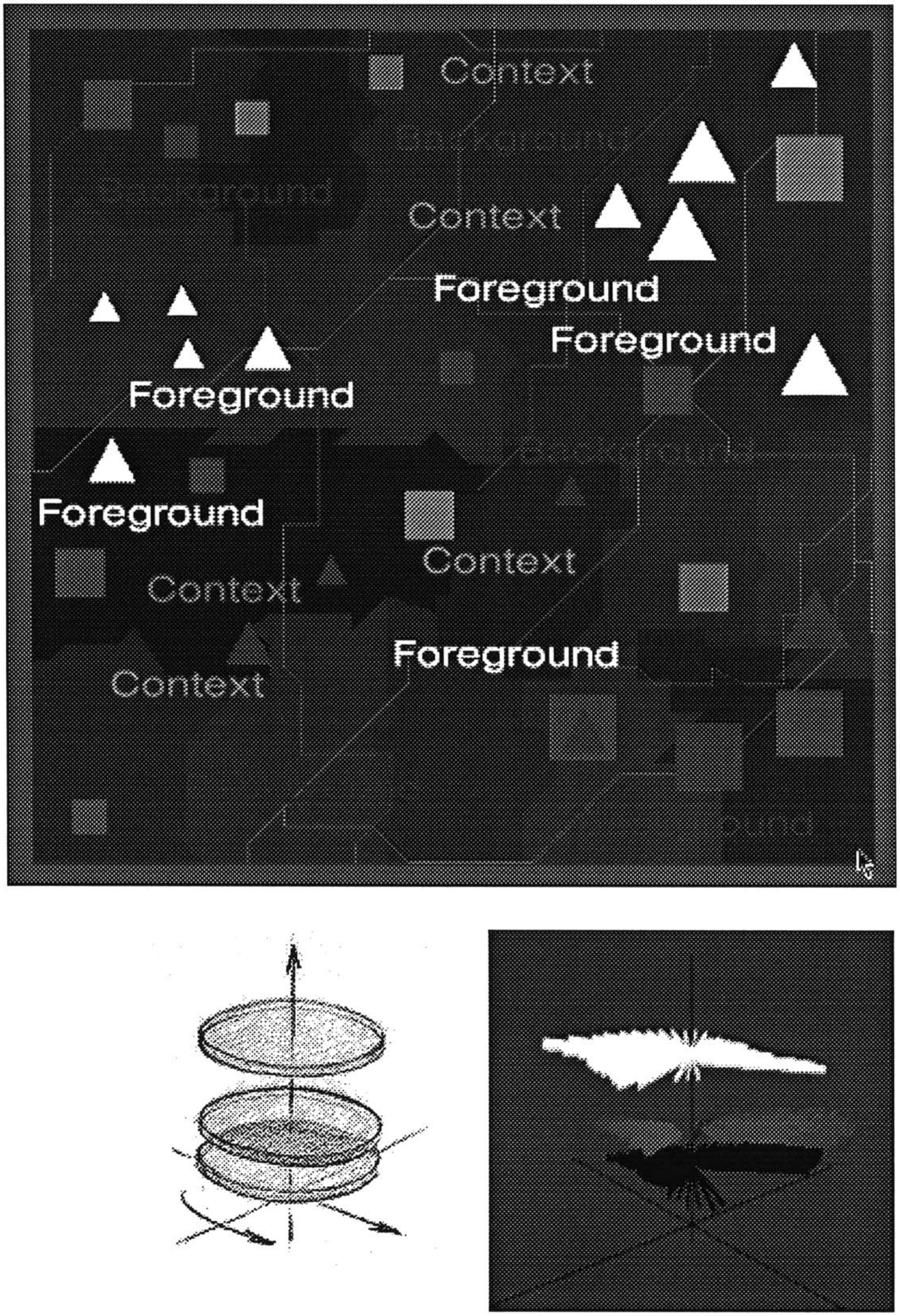

Figure 37. Example1. The restrictions are applied on value only.

The difficulty in creating the levels resides in the presence of the full range of chromaticity (full range of chroma and full range of hue) at every level. In this case, the only means of perceiving visual categories is similarity in value. As a result, visual level appear only when the zones become narrow in value, and the graphic objects contained in a given level become almost equiluminant. But the equiluminance of the objects at the same level is not sufficient to create clear visual categories. Since the full range of chroma is available, low and high chroma objects are present within the same level. The high chroma objects are perceived as having more salience than the low chroma objects. The high chroma context objects have a tendency to be perceived as part of the foreground level. The low chroma context objects have a tendency to appear as part of the background level. As a consequence, the context level visually dissolves in the image. To avoid this confusion, large distance has to be enforced between the zones.

Even though three distinct visual levels were finally established, the resulting image configuration has little potential for dynamic mapping. The first disadvantage of this configuration is a consequence of having to over-constrain the use of value in the image. As a result of color zones with a very narrow extent in value and value cannot be used, within a given level, to represent features or to provide differentiation between shapes. This is an unacceptable handicap in view of the important role that value contrast plays in the perception of shape. It is especially limiting at the background level where the graphic objects fill the 2d-space. The boundaries of objects are then indicated only by hue and chroma differences which are not sufficient to create easily perceivable edges.

The second disadvantage is related to the need for large distances between the zones. These large distances push the foreground and the background zones to the top and the bottom ends of the Munsell color space respectively, where chroma is not available. In the foreground, the objects will be very light and, consequently, very salient, but their chroma will be low. Their colors appear bright but vaguely tinted. In the background, the objects are darker and have a low chroma. In turn, the context zone, since it is situated in the value midrange, has a lot of chroma available and its objects appear very colorful. The unfortunate consequence of this configuration is that most of the high chroma objects are in the context level. In such an image, the eye seems to concentrate on the context level that is the richest in chroma. The foreground and context levels form two distinct visual categories but they compete for salience. The foreground owes its salience to brightness. The context owes it to high chroma. This situation contradicts the visual level definitions of section 6.1.

The wide distance between the color zone also causes an extreme value contrast between the objects of the foreground and the background. Extreme value contrasts should be avoided in the mapping image because they have a negative effect on the perception of chromaticity. Hue and chroma nuances are difficult to perceive in the proximity of an edge with an extreme contrast in value.

This example is presenting here despite its lack of success. It was the first configuration to come to mind, and the most obvious. The author expected better results from it. It during the exploration of this configuration that the first hint of the important influence of chroma in the electronic image was observed. As stated above, it is difficult to group in the same visual category equiluminant objects (same value) if their difference in chroma is large. Further, the context level the initial configuration was the richest in chroma and therefore competed for salience with the brighter foreground level. This heavy influence of chroma on salience, a factor of confusion in this image configuration, is turned into an advantage in the following examples.

Example 2, value and chroma restrictions

The visual experiments presented here attempts to establish visual levels in the dynamic image by restricting both value and chroma. The three zones are allowed to use the complete range of hue. Restriction are applied on the value and chroma dimension.

The ability to control chroma makes the task of establishing visual levels much easier. The new configuration that the zone structure assumes is shown in the diagram and 3d-view of **figure 38**. Two important improvements over example 1 configuration are obtained.

• The entire zone structure is contained in a volume that does not include the high and low end of the value dimension.

• The foreground zone is contained in the region of the color space that is the richest in chroma.

These improvements are possible because the sensitivity of the human eye to chroma differences is put to use to control the relative saliency in the image. In the first experiment, relative saliency is controlled only with value. The levels that need more salience are assigned higher values. In this experiment, value and

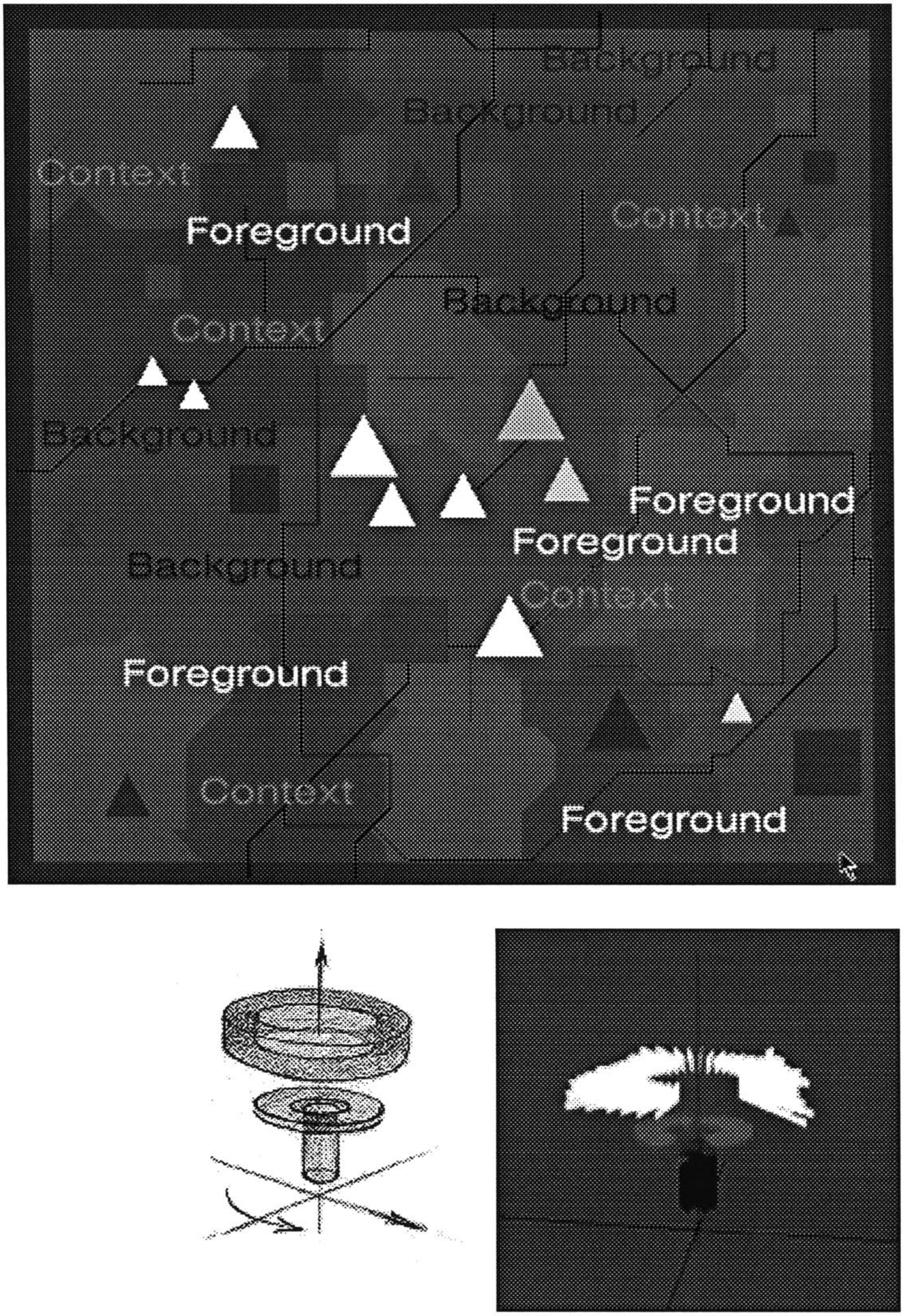

Figure 38. Example2. The restrictions are applied on the value and chroma dimensions.

chroma are combined in such a way that their influence on the relative saliency in the image are added. A higher salience is achieved by a joint value and chroma increase. With this combination, a similar range of saliency can be covered by using a smaller range of value. As a consequence, color zones can be closer together, and the zones can be brought into the most usable regions of the color space.

This new flexibility in the choice of color zone locations is a useful frame work for the dynamic image. An examination of the three visual levels in the resulting image of **figure 31** reveals the potential for dynamic mapping offered by this color zone configuration. The background level occupies the low end of the chroma dimension. This creates a well defined visual category. The constraints on color usage applied by the background color zone leave enough flexibility to represent the topography efficiently. The zone location, higher in the color space than in the first experiment, produces a globally brighter background image. As a result, the hues are perceived better. The extent of the zone in value (from 2.0 to 3.5) allows enough value contrast to represent shapes. By combining these limited ranges of value and chroma contrast with a full hue range, an intelligible background image can be build that still recedes enough to leave room for the dynamic operations of the upper levels.

The context level zone occupies a region narrow in value, close to the high end of the value range of the background zone. Its chroma extent is also located in the middle region of the chroma dimension. The graphic objects contained in the context level form a visual category because of their similarities in value and chroma. In turn, their hue is unrestricted. The visual category defines a clearly distinguishable visual level that is intuitively perceived as contextual. The level's narrow and higher chroma range differentiate its objects from the background object, but its relatively low value keeps these objects close to the background in salience. These characteristics fit the requirements of a context visual level. The contextual objects appear in a visual category that is separated from the background, but recedes to a level of salience that is close to the background. They never compete for attention with the foreground objects. This requirement was not achieved in the previous example. In this example, however, a chroma difference allows to achieve that subtle level of salience for the context level.

The foreground level is located in a region of the color space where chromaticity is the most perceivable. It occupies the middle to high end of the chroma dimension. Its extent in value is comparable to the extent of the background level. The value in the region is sufficiently higher than in the context and background levels to contribute to the salience of the objects, but not high enough to cause losses in chroma. Thus, the graphic objects can take a high chroma specification, regardless of their hue specification. As a result, the objects at this level form a very distinct visual category. Their salience is higher than all other objects in the image and hence the foreground level is immediately perceived as being principal part of the image. It is perceived as the center of the semantic activity, which fits the definition of a foreground visual level.

With this combination of restrictions on value and chroma, the color zones, i.e., the visual levels, provide an intuitive visual ordering to the dynamic image. A joint increase in value and chroma is intuitively perceived by a subject as an increase in salience and importance. A subject presented with an image ordered in such a way, is able to parse and identify the three levels without learning a color code or a convention. There is a lot of evidence in fine arts and graphic design that such a color combination affects a viewer in this predictable way. Testing this image configuration dynamically brings more evidence. When a group of graphic objects is moved from the context level to the foreground level, the visual effect of the move is striking. All the objects of the group increase both in value and chroma, retaining their hue. They are perceived as awakening from the dormant state they were in as part of the context, and join the action already taking place in the foreground. The opposite move, foreground-to-context, can be described with the same metaphor. A dynamic dimension is added to the concept of visual ordering. In the static mode, the image is organized by its visual levels. Their role is intuitively perceived. In the dynamic mode, the level-to-level moves are intuitively identified as increase or decrease in relevance to the main focus of the dialog that takes place between the user and the image.

The success of this color zone configuration comes with some drawbacks in the maintenance of graphic quality. Simultaneous contrast aberrations could be noticed between the context and the background level. Graphic objects in the context level tend to change color appearance when they are relocated on the background. The context and the background objects form two distinct visual categories despite the fact that the respective color zones are close by in the color space. With this closeness the color variations due to simultaneous contrast becomes perceptible. This is because the color differences that are used to differentiate the two categories are of the same magnitude than the variations due to simultaneous contrast. This problem was addressed by attempting to find a better distribution of color in the background. By limiting the contrast between the areas, and reserving the low values and high chromas for smaller object (lines, icon, text labels), the context objects appearance was protected from the influence of simultaneous contrast, and constancy was achieved.

The potential of chroma as an important variable for the control of saliency in the dynamic image comes also with a draw back. The 3-d representation of the Munsell color space **(figure 13, chapter 3)** shows that chroma is not evenly distributed within the entire color space. For every different hue-value pair, the maximum chroma level available is different. For instance, light yellows offer a wide range of chroma, light blues a very narrow one. In the visual level configuration described in this experiment, the foreground level uses the high end of the chroma range. Despite the fact that the part of the space where the most chroma is available is used, there remain irregularities of chroma distribution. These irregularities can cause some foreground objects to have chroma specifications much higher than their siblings and therefore to have more salience and appear as forming another visual category. This problem was addressed by pruning the high end of the chroma range in such a way that the maximum chroma specifications available to the foreground level is equal for all hues and values. **Figure 32** explains that pruning.

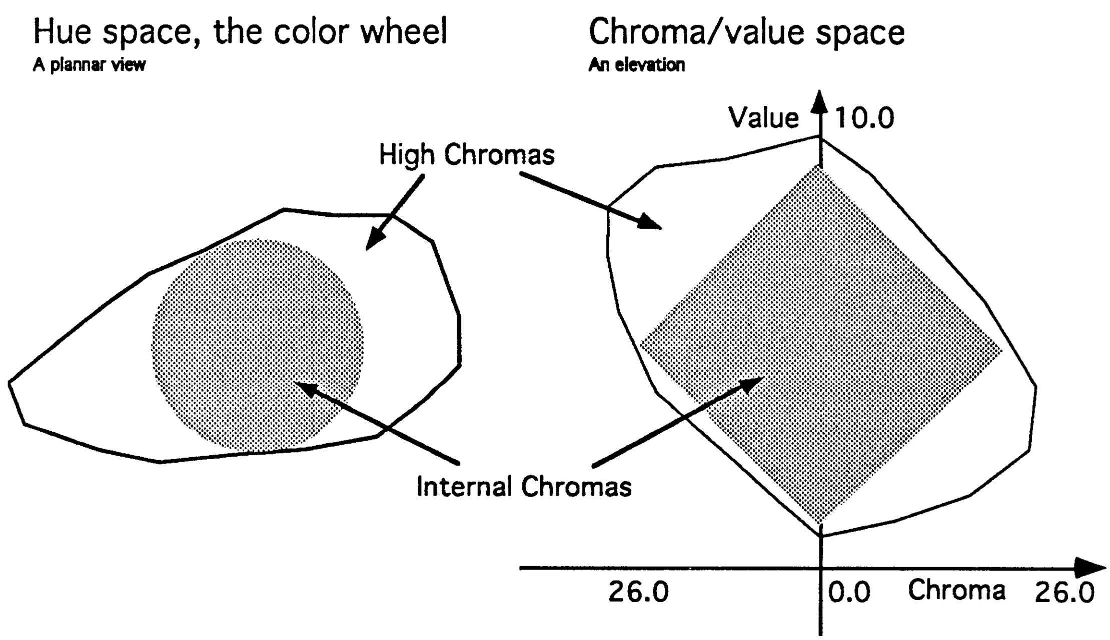

Figure 39. Chroma is not evenly distributed in a perceptually consistent space like the Munsell color model. The same levels of chroma are available for every hue in the *internal chromas*. In the *high chromas*, chroma levels are available only for a selection of hues.

Figure 39 also illustrates a principle that addresses the problem of the irregular distribution of chroma in perceptually consistent color spaces. The principle differentiates between *internal chromas* that are usable for the control of visual ordering and *high chromas* that are usable only for special purposes like highlighting or forming special visual categories. The internal chroma levels are reliable for visual ordering because each is available at every hue and value. At these chroma levels, groups of objects can be formed with equal chroma. The high chroma levels can be used for special purposes because they are available only for certain hues and values. The colors in these regions have very high chroma and can be made very salient, but they have few homologues in other parts of the space. Their control has to be treated differently than the color at internal chroma levels.

Example 3, restrictions on the three dimensions of color

In this third example, hue restrictions are added to the value and chroma combination explored in example 2. The purpose of this third experiment is to find out what advantages can be gained by having the different levels occupy different ranges in the hue dimension. Two advantages are expected:

• Further enhancing the differentiation between visual levels. The hue differences reinforce the differentiation obtained by chroma and value.

• Make a better use of the irregular distribution of chroma in the Munsell space. By restricting color zones in the hue dimension, the region of the space with higher chroma available (for instance: light yellows or dark blues) are brought into the zone system.

The zone structure that results from this experiment is shown in the diagram and 3-d view of **figure 40**. The value and chroma restriction are similar to the restriction of example 2. The hue restrictions are used to reinforce the differentiation between the background and upper levels. The background level is assigned a limited range in the hue dimension, while the upper levels use a wider yet symmetrical hue range . Gaps exist between the two hue ranges insuring that no similarities are possible between the background hues and those in the upper level.

Hue restrictions greatly improve the differentiation between the background level and the two upper levels. The improvement from this addition is apparent in a comparison between the resulting images of experiment 2 and 3 **(fig 39, 40)**.

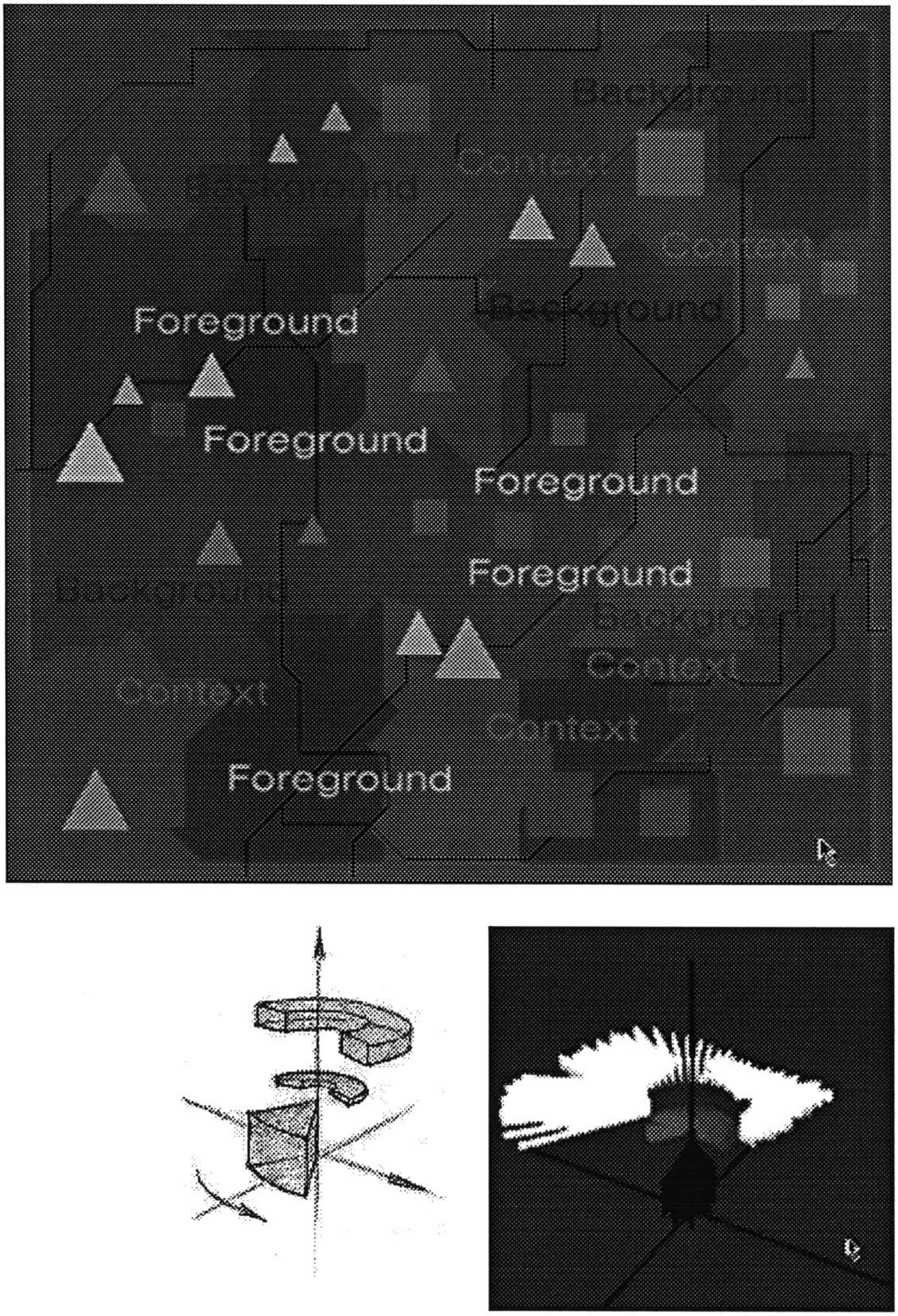

Figure 40. Example 3. Restrictions are applied on the three components of color.

Two high-level visual categories become apparent in the image of example 3, the category containing the upper level and the category containing the background. By keeping upper levels more visually separated from the background, increased flexibility is brought to the background color usage.

With this hue distribution, the background image becomes monochromatic. All the colors used at that level belong to the same hue category, in this example, the blue hue sector . As a consequence, the background graphic objects form a visual category that is different from the upper levels. All objects with a blue hue and a lower value are intuitively perceived as belonging to the background level. The image does not use the region of the color space that contains the lighter blues. This is not a limitation, since the lighter blues do not offer a wide chroma range. Using these color would only bring confusion between the upper levels and the background.

Restricting hue in the background level to a single hue category might appear very limiting. Paradoxically, the hue constraint allows the background color zone to have a lot more extent in chroma and value. On the diagram of **figure 40** the color zone assigned to background appears larger than for the previous examples. More flexibility is available in value and chroma to represent topographic information. This constitutes the main improvement brought by this color configuration. If chroma and value contrasts are appropriately distributed among the background objects, greater contrast can be used in the background without causing visual competition with the upper levels .

The experiment shows that a proper distribution treats large spatial-extent objects differently from small spatial-extent objects:

• Large spatial-extent objects (areas) have low chroma specifications. Small value contrast is enforced between them.

• Small spatial-extent objects (lines, icons, text labels) have higher chroma specifications. Higher contrast in value is maintained between these objects and the areas.

The chroma of the areas is kept low because of the high salience that chroma gives to an object, even at low values. Areas, with their wide spatial extent, become very salient as soon as their chroma level goes above the midpoint of the range. In these cases, they start to compete with the upper levels. To form a continuous image, the areas should appear at the same depth in the image. This is why the contrast in value among them is kept low, and their value is kept at the midrange of the background color zone. As a result, lines, icons and text labels belonging to the background can be either lighter or darker than the areas, and their chroma can be either higher or lower. With this color distribution in the background level there is a potential for a rich, monochromatic topographic image.

The advantages afforded by this color configuration come with two principal compromises:

• The color configuration assumes that no transfer of objects between the background and upper levels will be necessary to the semantic activity of the map.

• Topography, in some situations, might not be completely representable with a monochromatic image.

The first compromise, a "semantic separation" between upper levels and background results from the particular distribution of the hues. Hues available in both upper levels are not available in the background. The converse is obviously true. An object in the upper level cannot be moved to the background without losing its hue, which means losing part of its identity, since hue is used to express membership in a group. The problem can be addressed by noticing that, in most cases, a semantic separation between upper level and background exist in dynamic mapping. The topographic information imbedded in the background is static in nature, and serves as an informative backdrop. The relative saliency of its objects may need to be modified, but they always will have to be perceived as part of the topography and will not need to be transferred to the upper levels. Conversely, the objects in the upper levels represent information that is dynamic in nature. Transfers between the to upper levels are an important part of the dynamic activity in which they are involved, but there are few reasons for them to become part of the background.

The second compromise, the limitations of a monochrome topography, can be addressed by looking for ways to relax the hue constraint. If a monochrome image is too restrictive, carefully chosen sets of colors can be added to the background zones. As a result, a monochrome image would be replaced by an image with strong dominance in a particular hue category. This could be achieved by extending the hue range on both sides. The new colors could be used when hue differences are needed, but the dominant hue (blue in this example) would be used for most objects. The visual categorization occurring within the monochromatic image would still be achieved.

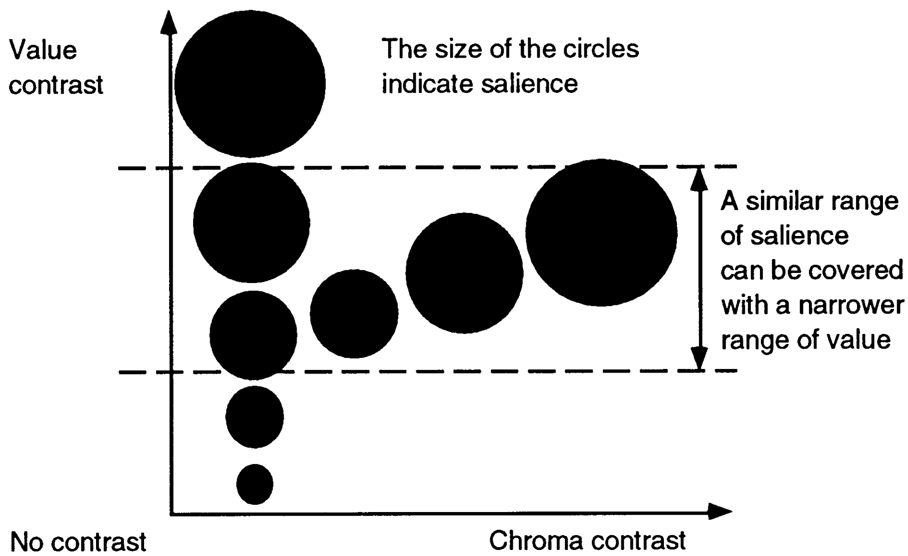

Figure 41. A similar range of salience can be covered with a combination of value and chroma contrast. As an advantage, the value range can be much narrower. (This diagram illustrates the tendency and does not present hard data)

3. Evaluation of the experiments findings

The findings of the experiments presented in this chapter validate the claim for the multiple roles of color in the dynamic image, which constitute base of this research. The findings also determine the scope of the control afforded by the color container/color zone method. They make apparent the need for an extension to a deeper, finer control.

Experiment 2 and 3 illustrate that a valid visual framework can be built in the image using the task distribution proposed in this work's hypothesis. Intuitively perceptible levels are created in the image by restricting the use of value and chroma at every level. The visual levels establish visual ordering and contribute to graphic quality. In both examples, enough leeway is given to the hue component to allow it to be used for grouping and association tasks.

Besides validating the hypothesis, the experiments help define the relative role of value and chroma in the establishment of visual ordering. The first experiment, shows that value cannot perform the task alone, and elicits the power of chroma as a salience factor. The diagram of **figure 34** presents a comparison between the ranges of saliency covered by value contrast alone and by the combination value and chroma contrasts. In examples 2 and 3, this power is successfully put to use. The principal role that chroma has to play in the establishment of visual levels is demonstrated. The experiments also suggest that, besides a purely visual salience, chroma provides a "semantic salience." Object groups with a higher chroma level have more importance in the image. Such a feature is important to dynamic mapping, as the system must reinforce the signification of every visual modification. As subjective as this finding may appear, recent results give them fundation. Work on quantifying color relatedness is currently being performed by Feldman. In this work, the effects of hue, value, chroma, size, shape and proportion of graphical elements on the way colors are experienced has been measured. It has been found that what matters in color experience is the relationship between colors, and not the individual colors of the graphic elements. Chroma contrast has a strong effect on subjects. Increasing the chroma of graphic elements increases their prominence. Visual prominence can also be enhanced by adjusting value contrast between elements, i.e., colors are more colorfull (more chroma is perceived) when the value contrast is small [Feldman, 1992].

The knowledge that has been gathered with this series of experiments can be considered as general principles for the visual framework that organizes dynamic mapping. The color zones provide a broad partition of the color space that allows a global visual ordering. Within each zone, the allocation of color resources to different objects' categories is a determining factor for the success of the image. For instance, in example 2, a careful distribution of chroma among the four graphic categories insures that the background image efficiently represents the topography . Therefore, the control of color in the dynamic image must also be applied at a finer level. Color zones must be given sub-structures that govern the distribution of color resources among the object groups they contain.

Experiments remains to be conducted with graphic situations closer to real mapping situations. The current system supports this kind of images, but it appears that the color container/color zone system requires more development to provide control that goes deeper than global color relationships.

Chapter 7. **Conclusion**

"Quand il faut tant de mots pour le dire, tout cela s'embrassait d'un seul regard , ou plutôt, de mille regards ä la fois et dans le même instant."

Louis Gilloux, Le pain des rêves.

The research work presented in this thesis is based on the hypothesis that the three components of color, in a perceptually consistent color space, can play complementary roles in the dynamic mapping image. The hypothesis, illustrated in the diagram of **figure 6,** states that the value and chroma components of color can be used to build a visual framework in the image. Concurrently, the hue component can be used to perform the semantic tasks that are usually assigned to color, association and selection.

The visual framework has two principal purposes.

• Providing *visual ordering,* a visual organization of the image that reflects its semantic organization. Visual ordering, in static images, helps the viewer parse the image components easily. It insures that visual confusion does not stand in the way of the image understanding. In dynamic images, visual ordering is primordial. It is a necessary condition to the dialog that takes place between the user and the dynamic image.

• Helping to support *predictable color modifications.* As the dynamic mapping image evolves, its color are modified to achieve visual effects. These effects are related to the control of the graphic objects relative salience. The predictability of color modifications insures that the modifications' intention are consistent with their visual effect on the viewer.

The research undertaken for the validation of this hypothesis brings forward three important aspects in the control of dynamic mapping images:

• The need for a method of management of *color relationships*

• The practicality, for dynamic images, of the *relative storage of color specifications*

• The possibility of *acquiring and developing visual and graphic knowledge directly*, without relying on verbalization.

Graphic control of color supposes the control of color relationships. This idea is basic in the field of visual design [Albers, 1972]. It is emerging in the field of computer visual communication , for instance, in the work of Bender et. al. [Bender, Jacobson, 1991]. It became quickly evident that the hypothesis proposed in this thesis could be validated only in an image within which all color relationships were controllable. The method of color relationships management is, therefore, the principal component of the work. It is based on the simple mapping relationship that exists between an image and the color space that supports it. The simple mapping relationship is organized as a projection of the image semantic structure into the color space. *Color containers* bring into the projection the groupings and categories of the image. The color containers are used as vehicles to transport the color specifications of graphic objects group across the color space. With their help, color modifications can be applied at every levels of the image organization. *Color zones* are used to partition the color space. They determine the parts of the color space that can be used by the image; they establish the visual levels of the image. They also guide the evolution of the color containers in the color space. With the combination of color containers and color zones, the global color relationships of the image are controllable.

The graphic application system that was developed supports a prototype dynamic image. Its color relationships are controlled by an implementation of the proposed color management method. The visual framework necessary to dynamic images has been successfully established by applying sets of restrictions on the usage of the three component of color. In these images, color plays the multiple role that the hypothesis claimed it should play. The hue component is usable for association and selection tasks while, concurrently, value and chroma are used for the establishment of visual ordering and the maintenance of graphic quality. The prototype image was given a level of complexity sufficient to approximate the visual situation encountered in electronic maps. The visual ordering that is established is only global. Nevertheless the author wish to assert that the results of the visual experimentation are convincing enough to validate the hypothesis.

A second aspect relevant to the control of the dynamic image was brought forward in the course of this work. In addition to both RGB and Munsell absolute specifications, the graphic objects data structure keeps track of a normalized Munsell vector; a specification relative to the color containers. This relative specification is actually storing the relationship of the objects' colors to their container. As a consequence of the same process, the color relationship between the objects of a group are represented as well. This relative storage of color specification is very useful to dynamic mapping images. It implies that a commitment is made to store only color relationships, i.e., color constellations, rather than a final color specification which constitute only one of their representation. With such a representation, color constellations can be freely moved across the color space, their shapes and amplitudes can be modified. A commitment to a final color specification is made only at display time, which allows the flexibility in color control that is required for dynamic mapping. When this storage method is applied to bitmaps, their appearance can be controlled at will. The image they contain can be concealed, attenuated or revealed. A single bitmap can be displayed with many different appearance, according to the need of the current situation.

The color management method ultimate purpose is to serve as a control structure for an automated color management module. This purpose is achievable only if visual and graphic knowledge can be acquired, and applied by the method. The series of visual experiments proved that the method is efficient at applying the visual and graphic knowledge supplied by a graphic designer. By interactively controlling the prototype image color relationships, the a graphic designer was able to use his expertise to give the image the required visual framework. This process appears to constitute also an efficient method of knowledge acquisition for the automation of graphic control. The experimental procedure described in chapter 6 can be viewed as a knowledge acquisition process where an expert in visual matters is given the control of the prototype dynamic image. The recorded actions of the expert constitute a knowledge base that can be used to automate the control process.

Such a knowledge acquisition process, by avoiding the mediation of verbalization, allows the expert graphic designer to react directly to the new visual situations offered by dynamic images. The designer can apply the expertise acquired in controlling complex images in other media. Most importantly the designer can develop new expertise, specific to the electronic medium by directly practicing their control. It seems that the need for this type of knowledge development will increase as the electronic medium becomes more and more able to support real visual communication. Visual designers, whose main contribution is to bring together image production technologies and the communication of ideas, will need the means to experiment directly with the electronic images. The experimental graphic application that was developed with this thesis and the series of visual experimentation that it made possible constitute an example of such a knowledge development process.

This research work attempted to contribute to the development of dynamic mapping images by concentrating on the graphic problems that come with an evolving color situation. It is was initially noticed that, as all images with a clear purpose of communication, the semantic structure of the dynamic image has to be reinforced by its visual structure. It was also noticed that an evolving visual situation was likely to create unnecessary graphic conflicts. Looking at color usage in traditional mapping, and acquiring an understanding of the controllability of color in the electronic medium lead to the hypothesis that color could play a principal role in building the visual framework that was necessary to dynamic mapping.

The management method that was developed and the experimentation that was conducted validates the hypothesis that was made. It also serves to elicit the extent of the research work that is needed before the full potential of dynamic mapping can be realized. The management method that was developed provided a global control of the image color situation. Experimenting with it made apparent the need for a finer control of color. A more detailed control of the image implies a that more visual and graphic knowledge will have to be acquired. It is fulfill this need for more detailed control and finer graphic knowledge acquisition that this research will be pursued.

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Traductions

Chapter 1, page 7.

"Color, say the physicists, is a property of of light which cause, according to the different configurations and speed of its particles, vibrations on the optical nerve, which being propagated to the sensorium, affect the soul with different sensations". Diderot wrote the Encyclopdie in the mid-seventeen-hundreds.

Chapter 3, page 25. "I am against the color that hides incompetence, and I remain against it as long as it will be believed to suffice for the representation of an order..."

Chapter 7, page 103. "When so many words were necessary to say it, all this could be grasped in a single gaze, or rather, in a thousand gazes, in a single instant."